Series II, Volume 6 March 20, 1961 Number 2

BULLETIN

OF THE

AMERICAN PHYSICAL SOCIETY

INCLUDING THE

PROGRAMME OF THE

1961 MARCH MEETING

AT

MONTEREY, CALIFORNIA

March 20–23

PUBLISHED BY THE AMERICAN PHYSICAL SOCIETY, COLUMBIA UNIVERSITY, NEW YORK 27, NEW YORK
SIX ISSUES EACH YEAR

BULLETIN

of the

AMERICAN PHYSICAL SOCIETY

Published six times per year

Subscription price: $5.00 per year

Back number prices: $4.00 for the triennial Membership List; $1.00 for other issues.

The Bulletin of the American Physical Society is published six times a year, once in February, once in March, once in April, once in June, once in November, and once in December, at Prince and Lemon Streets, Lancaster, Pennsylvania. Correspondence should be addressed to American Physical Society, Columbia University, New York 27, New York.

Second class postage paid at Lancaster, Pa.

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March 20, 1961 Series II, Vol. 6, No. 2

BULLETIN

OF THE

AMERICAN PHYSICAL SOCIETY

1961 "March" Meeting in Monterey, March 20–23, 1961

FOR the first time in the colorful history of the West, the 1961 **"March" meeting of the American Physical Society,** from Monday, March 20, through Thursday, March 23, will bring an unprecedented migration of 412 contributed and 46 invited papers to Monterey, at the U. S. Naval Postgraduate School, California. The Divisions of Solid-State Physics, Chemical Physics, and High-Polymer Physics have established the main theme of subjects, therefore drawing upon a large number of "Easterners." This meeting will exceed in size all previous West Coast and "March" meetings and threatens to approach the size of a New York meeting. Special thanks are due to A. M. Portis, who played a major role in distributing the abstracts into their proper sessions, and to D. W. McCall, who efficiently arranged the sessions in High-Polymer Physics. There will be a session of four invited papers in Nuclear Physics, arranged by J. Blair, and a session of contributed papers for those nuclear physicists who are brave enough to attend as a minority group. We are indebted to the local committee at the Navy School, consisting of Professors J. R. Neighbours, *Chairman*, J. N. Cooper, and L. O. Olsen, who are bearing up nobly under the tasks of organizing local arrangements in Monterey. Thanks are due to E. Burstein, retiring this year from active duty for the Solid-State Division, to J. H. Van Vleck, C. Herring, R. J. Maurer, D. W. McCall, and H. M. McConnell for arrangements of invited papers of the various Divisions, and to J. Blair for arrangement of the Nuclear Physics session. There is sufficient though perhaps marginal space at the Navy School to handle no more than six parallel sessions, which accounts, unavoidably, and to our regret, for an unusual number of long sessions extended over four days.

The Monterey Peninsula Convention Bureau assures us that **room accommodations** for at least 1200 persons will be available. Accommodations are reasonably close to the Navy School, which is on Fremont Avenue. These accommodations consist mainly of motels stretched along Fremont Avenue, east of the school, and motels along Munras Avenue, which intersects with Fremont Avenue and extends southwest of the School. Write immediately for rooms, if you have not done so, to the Monterey Peninsula Convention Bureau, P. O. Box 489, Monterey, California, and be certain to state you are attending the meeting of the American Physical Society. It will be helpful, for the organization of the Ladies' Programme, if you will indicate if you will be accompanied by your wife. Your room choice will be considerably assured if you enclose a check for a nominal amount, state your arrival and departure time, nature of accommodations, and special areas if desired, such as Carmel, Pebble Beach, or Pacific Grove, assuming you have your own transportation. State specifically if you wish to be assigned to the motel rooms mentioned above. It will be helpful to know your mode of transportation.

For those assigned to these motel rooms, **special shuttle buses** marked "Charter" will travel between the Munras Avenue-Soledad Drive corner and the Navy School, and Fremont Avenue-Airport Road corner and the Navy School. These buses will shuttle continuously during the times between 8:30 and 10:00 a.m. and 4:45 through 6:45 p.m., if necessary, for all four days of the meeting. These buses, passing by at 15-min intervals, may be flagged down and boarded on the safe side of the road as they pass your particular motel. It is requested that those who wait should cluster together and board in groups in order to save time. We note that taxicab service is available, but that there are only about 30 of them in the entire Monterey Peninsula. It is economical and convenient for at least four people to share a car rental at $10.00 per day at 10 cents a mile, with gasoline included. This is suggested for those who would like to drive from San Francisco Airport directly to Monterey, taking about two and one-half hours.

Access from the East to Monterey is best through Oakland. Excellent trains, the "California Zephyr" and the "City of San Francisco," leave the Union Station in Chicago in the late afternoon (the latter also from the Union Station in St. Louis) and arrive at Oakland the next day but one. From Oakland transfer is made by railroad-operated bus to the Third and Townsend street station in San Francisco, from which the "Del Monte" leaves for Monterey at 6:25 p.m. Those coming via Los Angeles should take the "Daylight" of the Southern Pacific and change to a bus at Salinas: this is also practicable for those who arrive at Oakland and wish to spend the night in San Francisco.

There are a number of daily flights from San Francisco to Monterey. Pacific Airlines service between Los Angeles and Monterey is assured by several daily flights. Greyhound Bus service is available almost hourly through the twenty-four hour period from San Francisco to Monterey.

Registration will take place in the lobby of Spanagel Hall on the grounds of the U. S. Naval Postgraduate School. Spanagel Hall is best reached by entering the gate on Sloat Avenue, very near the intersection of Sloat Avenue and Fremont Street, which is also State Route 1. Spanagel Hall is directly ahead of the entrance gate. Parking will be supervised by campus police, and the routes to various buildings used for sessions will be well posted. Maps of the campus will be available upon registration. The **registration fee** will be two dollars, which exceeds the usual one dollar in order to provide shuttle bus service.

For the **invited papers of the three Divisions** the reader is referred to the Main Text and the Epitome. Special mention, however, is accorded to the **Oliver E. Buckley Lecture** to be delivered on Tuesday morning at 11:00 in King Hall by Walter Kohn, the latest to receive the Oliver E. Buckley Solid-State Physics Prize. The Division of Solid-State Physics has succeeded in copying the precedent of past years by so disposing its sessions that none of them coincides in time with this event.

Luncheons will be available every day of the meetings at the King Hall cafeteria, the Bali Room cafeteria in Herrmann Hall, and at the Snack Bar in Herrmann Hall. It is requested that a rush period involving Navy personnel between 12:00 and 12:30 p.m. be avoided, since the Navy School will be in session. On Tuesday, Wednesday, and Thursday, luncheon will be served in the East Bali Room of Herrmann Hall for those who have purchased tickets at the Registration Desk. The ticket sale for each day's luncheon closes on the afternoon of the preceding day. Not more than 250 can be accommodated for this particular luncheon. The Mark Thomas Inn, directly opposite the Navy School, can accommodate about 150 people for luncheons. Breakfasts (limited menu) are served in the cafeteria in King Hall and at the Snack Bar in Herrmann Hall. Also, with the compliments of the Fisherman's Wharf Association and the Convention Bureau of Monterey, two shuttle buses will be available for taking people to and from restaurants in Monterey and Fisherman's Wharf for lunch. A list of excellent restaurants on the Monterey Peninsula will be available at the Registration Desk.

The **banquet of the Society will be held on Tuesday evening** in the Bali Room, Herrmann Hall. The price will be four dollars. F. Seitz, the new President of the Society, will preside. The **banquet speaker** will be Robert Herman of the Research Laboratories, General Motors Corporation, who will speak on the subject of "Traffic—Old and New." The banquet hall cannot accommodate more than 450 people. The deadline for the last ticket sale is Tuesday noon, and you are advised to purchase your ticket as early as possible, and certainly by mail if you arrive late on Tuesday. Make your check out to the American Physical Society, care of Professor J. R. Neighbours, U. S. Naval Postgraduate School, Monterey, California.

A **cocktail party** will be held in the Ballroom of Herrmann Hall from 6:00 to 7:30 p.m. before the banquet. Unless sponsorship for the party is obtained before the meeting time, those who wish to attend the party will be assessed $1.50 by the sale of tickets at the Registration Desk.

Details of a **programme for the ladies** will be available at the Registration Desk. In brief, on Monday a walking tour of historic Monterey is planned with Fisherman's Wharf at hand for lunch. On Tuesday, Mrs. Austin R. Frey, wife of the Navy Physics Department Chairman, will entertain the ladies at home in Pebble Beach. Transportation will be provided. On Wednesday, a bus tour of Monterey Peninsula includes Cannery Row, 17 Mile Drive, Carmel, Carmel Mission, with luncheon enroute. Ladies must sign up to be certain of a space.

The Council of The American Physical Society will meet at a time and place of which its members will be notified. Unless an emergency arises, this meeting will be devoted to ordinary business such as action upon candidacies for Fellowship and Membership.

There will be **Business Meetings of our three Divisions** at the times and places indicated in Epitome and Main Text.

Post-deadline ten-minute papers pertaining to very recent achievements of very special importance will be considered for admission to the "special supplementary programme" if the abstracts are received not later than Friday, March 10, at the office of Professor E. L. Hahn, Department of Physics, University of California, Berkeley 4, Calif. Type at the top of each such abstract the words "POST-DEADLINE ABSTRACT FOR MONTEREY MEETING." The titles of such as are accepted will be written on blackboards near the Registration Desk, together with the sessions to which they have been assigned.

Errata pertaining to the contents of this issue will be published in a later issue of the Bulletin if received not later than Monday, March 27, by Miss Ruth F. Bryans, American Institute of Physics, 335 East 45 Street, New York 17, New York. Do not send in a copy of your abstract marked with corrections. Write out your corrections in the form "Instead of . . . read. . . ." or, if you prefer, "replace the sentence beginning with the words . . . by the following sentence. . . ." Add nothing.

E. L. HAHN, *Deputy Local Secretary for the Pacific Coast*
University of California
Berkeley 4, California

EPITOME OF THE 1961 MONTEREY MEETING

(Personal names are those of invited speakers. DSSP stands for Division of Solid-State Physics, DHPP for Division of High-Polymer Physics, DCP for Division of Chemical Physics.)

Monday Morning

9:30	A.	Nuclear magnetic resonance. Terrace Room, Mark Thomas Inn.
9:15	B.	Semiconductor junctions. Criscuolo Hall.
9:30	BA.	Philips; Band theory, x-ray and electron scattering. Ballroom, Herrman Hall.
9:30	C.	Photo effects. Copper Cup Room, Herrmann Hall.
9:30	CA.	DSSP symposium on magnetism of rare earth metals and compounds: Kaplan, Wilkinson, White, Meyer. King Hall.
9:30	D.	Color centers. 400 Spanagel Hall.

Monday Afternoon

1:30	DA.	Javan, Glicksman; cyclotron and magneto-plasma resonance. Criscuolo Hall.
2:00	E.	Electron spin resonance I. Ballroom, Herrman Hall.
2:00	EA.	Theory. Copper Cup Room, Herrmann Hall.
1:30	F.	Superconductivity, helium. Terrace Room, Mark Thomas Inn.
2:00	FA.	Magnetism I. 400 Spanagel Hall.
2:00	G.	DSSP symposium on atomic properties; Rosenstock, Brockhouse, Klemens, Lazarus. King Hall.

Tuesday Morning

9:30	GA.	DHPP I: Pao, Porter, contributed papers. 421 Spanagel Hall.
9:15	H.	DSSP: Dieke, Elliott
11:00		Oliver E. Buckley Lecture by W. Kohn; Business Meeting of DSSP. King Hall.
9:30	HA.	Graphites. Copper Cup Room, Herrmann Hall.
9:30	I.	Galvanomagnetic properties of semiconductors. Ballroom, Herrman Hall.
9:30	IA.	Charge transport. Criscuolo Hall.
9:30	J.	Elastic properties. Terrace Room, Mark Thomas Inn.

Tuesday Afternoon

2:00	JA.	DHPP II: Gornick, Powles, contributed papers. 421 Spanagel Hall.
2:00	K.	Wertheim; Mössbauer effect. 400 Spanagel Hall.
2:00	KA.	Electron transport in semiconductors, thermoelectricity. Ballroom, Herrman Hall.
2:00	L.	Uehling; insulators I. Terrace Room, Mark Thomas Inn.
2:00	LA.	DSSP symposium on new effects and techniques: Matthias, Garrett, Fisher, Brout. King Hall.
2:00	M.	Low; electron spin resonance, hyperfine interactions, relaxation II. Criscuolo Hall.

Tuesday Evening

7:30		Banquet of The American Physical Society; Herman. Bali Room, Herrmann Hall.

Wednesday Morning

9:30	MA.	DHPP III. 421 Spanagel Hall.
9:30	N.	Metals. Ballroom, Herrman Hall.
10:00	NA.	Excitons, band edges. Criscuolo Hall.
9:30	O.	Reich, Goodkind, Lane, Alers; low temperatures. King Hall.
10:00	OA.	Nuclear physics. Copper Cup Room, Herrmann Hall.
9:30	P.	DCP I. Terrace Room, Mark Thomas Inn.

Wednesday Afternoon

2:00 PA. DHPP IV. 421 Spanagel Hall.

2:00 Q. Wilets, Wiegand, Walecka, Blair; nuclear physics. 400 Spanagel Hall.

2:00 QA. Schlosser; degenerate semiconductors and impurities. Criscuolo Hall.

1:30 R. Lieberman; defects in metals, annealing. Terrace Room, Mark Thomas Inn.

2:00 S. Jarrett; Magnetism II. Ballroom, Herrman Hall.

2:00 T. Chemical physics I, symposium on paramagnetic resonance and shifts; Hutchison, Weissman, McLachlan, Pake. King Hall.

Thursday Morning

9:30 TA. DHPP V: Berry, Blatz, contributed papers. Terrace Room, Mark Thomas Inn.

9:30 U. Dislocations. 400 Spanagel Hall.

9:30 UA. Chemical physics II. Copper Cup Room, Herrmann Hall.

9:30 V. Surface phenomena and crystal growth. 421 Spanagel Hall.

10:00 VA. Magnetism III, insulators II. Ballroom, Herrman Hall.

Thursday Afternoon

2:00 W. DHPP VI: Mandelkern, Hoffman, contributed papers. Terrace Room, Mark Thomas Inn.

2:00 X. Diffusion, internal friction. 400 Spanagel Hall.

2:00 Y. Abeles; thermal studies. Copper Cup Room, Herrmann Hall.

2:00 Z. Watkins; irradiation effects. 421 Spanagel Hall.

PROGRAMME

MONDAY MORNING AT 9:30

Terrace Room, Mark Thomas Inn

(M. PACKARD presiding)

Nuclear Magnetic Resonance

A1. Spin-Echo Attenuation in Generalized Diffusion Models. J. R. KLAUDER, *Bell Telephone Laboratories, Inc.*—The decay of multipulse spin-echoes due to diffusion of the precessional frequency $\delta(t)$ has been determined for a broad class of stationary Markoffian distributions defined by $P(\delta,t;\delta_0)=(2\pi)^{-1}\int \exp[i(\delta-\delta_0)\lambda-tf(\lambda)]d\lambda$. After a time interval t the envelope of the spin-echoes for an arbitrary sequence of 180° rf pulses is

$$\exp\left\{-\int_0^t f\left[\int_{t'}^t s(t'')dt''\right]dt'\right\},$$

where $s(t)=\pm 1$, s being initially $+1$ and changing sign at each pulse. In general, $f(0)=0\leq f(t)=f^*(-t)$; in particular, $f(t)=kt^2$ leads to the previously studied Gaussian diffusion[1] while $f(t)=m|t|$ leads to Lorentzian diffusion. Recent experiments[2] involving a low density of diffusion sites are fitted quite well by a diffusion law that is very nearly Lorentzian. The general analysis is readily extended to distributions such that $\langle\delta\rangle_{av}=\delta_0\exp(-Rt)$, which have been studied previously only for Gaussian diffusion.[3]

[1] H. Y. Carr and E. M. Purcell, Phys. Rev. **94**, 630 (1954).
[2] W. B. Mims and K. Nassau, Bull. Am. Phys. Soc. Ser. II, **5**, 419 (1960).
[3] B. Herzog and E. L. Hahn, Phys. Rev. **103**, 148 (1956).

A2. Interpair Nuclear Magnetic Relaxation in Hydrated Crystals.* D. F. HOLCOMB AND B. PEDERSEN, *Cornell University.*—We have carried out a set of pulsed rf spin-lattice relaxation time measurements on the proton system in $CaSO_4\cdot 2H_2O$. The measurements were performed at several crystal orientations, and over a temperature range from 160° to 365°K. A more limited set of measurements was performed on the Li^7 and proton systems in $Li_2SO_4\cdot H_2O$ powder. In both systems, there is a strong relaxation mechanism arising from dipolar motion. In the $CaSO_4\cdot 2H_2O$ crystal, we believe that this relaxation arises from 180° flips of the water molecules. The flip rate is thermally activated with an activation energy of 6.2 ± 0.5 kcal/mole, a reasonable energy for the two hydrogen bonds involved. There is essentially no narrowing of the proton resonance, in spite of the fact that the characteristic motional frequency reaches the Larmor frequency, 9.0 Mc/sec, at about 240°K. Interpair, rather than intrapair, interactions are responsible for the relaxation. The interpair interactions require that one mix singlet and triplet wave functions in order to adequately describe the system. A simplified calculation using only two interacting pairs in $CaSO_4\cdot 2H_2O$ indicates that the observed minimum value of T_1, 0.4 sec, is reasonably accounted for by the proposed mechanism.

* Supported in part by the U. S. Office of Naval Research.

A3. Nuclear Spin Relaxation in NaCl at High Temperatures. MAURICE EISENSTADT, *I. B. M. Watson Laboratory.*—Nuclear spin-lattice and spin-spin relaxation times have been measured for Na^{23} in a single crystal of NaCl from room temperature up to the melting point. Below 750°K, T_1 can be described empirically by $T_1=0.35+1.05\times 10^4 T^{-2}$ sec, with the exception of a small minimum due to vacancy diffusion at 540°K. Above 750°K, T_1 decreases more rapidly, and is 0.46 ± 0.04 sec at 1057°K. In this range both dipolar and quadrupolar relaxation due to Na^{23} diffusion can occur, and the recovery of the spin system towards thermal equilibrium following a 180° rf pulse is not exponential. Above 850°K, free-induction decays, as measured by the spin-echo technique, become markedly non-exponential, and can be well resolved into two exponentials, one about eight times faster than the other. At 1057°K, the values of the two decay times are 225 and 25 msec. Preliminary measurements on Cl^{35} will be discussed.

A4. Double Resonance Study of Relaxation in a Two-Spin System. G. A. WILLIAMS, *Bell Telephone Laboratories, Inc.*—The relaxation probabilities of individual transition in a high-resolution nuclear magnetic resonance spectrum have been studied using a double resonance technique. This technique allows measurement of the relaxation probabilities of the $\Delta m=\pm 2$, and $\Delta m=0$ transitions, as well as the $\Delta m=\pm 1$ transitions normally observed in magnetic resonance experiments. Quantitative data have been obtained for all six transitions in a two-spin four-level system, 2-bromo-5-chlorothiophene. The relaxation is not symmetric, demonstrating the influence of the bromine and chlorine neighbors. The advantage of the method is shown by the fact that direct observation of the recovery from saturation of the four observable transitions fails to show the asymmetry.

A5. Nuclear Magnetic Resonance in Intermetallic Compounds of Lanthanum. R. G. SHULMAN, B. J. WYLUDA, AND B. T. MATTHIAS, *Bell Telephone Laboratories, Inc.*—Nuclear magnetic resonance shifts in superconducting intermetallic compounds have recently been reported.[1,2] In the solid solution series $(LaRu_2)_x(ThRu_2)_{1-x}$, the superconducting transition temperature is[3] a function of composition with maxima in the vicinity of $x=0.9$ and 0.15 and a minimum around $x=0.5$. In these compounds we have measured the La^{139} resonance at constant frequency, which is shifted to higher magnetic fields showing a *negative* Knight shift. At room temperature the shifts reach maxima at $x=0.15$ and 1.0 and are smallest around $x=0.5$, correlating very well with the superconducting transition temperatures. At lower temperatures the shifts increase, e.g., for $x=1.0$; $(\Delta H/H)|_{300}=0.54\times 10^{-2}$ and $(\Delta H/H)|_{77}=0.94\times 10^{-2}$. In contrast to $LaRu_2$, negligible shifts of the La^{139} resonance are observed in $LaIr_2$, $LaRh_2$, and $LaOs_2$. Furthermore, in $LaPt_2$ a *positive* Knight shift of 0.77×10^{-2} is measured which is temperature independent to a first approximation. Since, of these compounds, $LaOs_2$ has the highest superconducting transition, i.e., 6.5°K, it is shown once again that this temperature and the negative Knight shifts are related[1,2] but not inseparable. This relation will be discussed.

[1] R. G. Shulman, B. J. Wyluda, and B. T. Matthias, Phys. Rev. Letters **1**, 278 (1958).
[2] W. E. Blumberg, J. Eisinger, V. Jaccarino, and B. T. Matthias, Phys. Rev. Letters **5**, 149 (1960).
[3] B. T. Matthias, V. B. Compton, and E. Corenzwit (to be published).

A6. Correlations between Superconductivity and NMR. Linewidths, Quadrupole Interactions, and Impurity Effects. A. C. GOSSARD, V. JACCARINO, AND J. H. WERNICK, *Bell Telephone Laboratories, Inc.*—Correlations between the superconducting transition temperature T_c and the temperature

dependence of the Knight shifts (k), the linewidths (δH) and the nuclear quadrupole interactions (e^2qQ) of the NMR in certain intermetallic compounds V_3X have been found.[1] Similar correlations between the susceptibility χ and T_s have been found and an interpretation of the relation between k_v, k_x, and χ has been given. The large low-temperature δH of V and Ga in V_3Ga is found to increase with increasing field. Although this large field-dependent low-temperature linewidth is absent in V_3Si and $V_3Si_{0.9}Ge_{0.1}$, its presence in $V_3Si_{0.9}Al_{0.1}$ confirms an indirect nuclear spin-spin interaction. The field dependence of the interaction was not expected. The high-temperature δH of the $V^{51}(\frac{1}{2} \rightarrow -\frac{1}{2})$ transition is shown to result from second-order quadrupole interactions in V_3Ga, V_3Si, and V_3Co. Unlike k and χ, e^2qQ in the high-temperature superconductors is temperature independent and is unaffected by Ti and Cr substitutions for V. The Al^{27} NMR has been observed in $V_3Si_{0.9}Al_{0.1}$ with $k^{27}<0$ indicating that nearest-neighbor interactions in the V_3X structure are dominant in determining the sign of k_x.

[1] W. E. Blumberg, J. Eisinger, V. Jaccarino, and B. T. Matthias, Phys. Rev. Letters 5, 149 (1960).

A7. Core Polarization Contributions to Knight Shifts and Hyperfine Fields. R. E. Watson, *AVCO, R.A.D.*, and A. J. Freeman, *Ordnance Materials Research Office.*—The Knight shift in metals is thought to arise from the contact hyperfine interaction between the nuclear magnetic moment and the field due to the unpaired conduction electrons and can be written as a product of the spin susceptibility χ_P and $|\psi_s(0)|_F^2$, the average value of s conduction electron density at the nucleus for electrons near the Fermi surface. This relation can also be expressed in terms of the free-atom hyperfine field H_a by introducing a parameter ξ which is the ratio of $|\psi(0)|^2$ in the metal to that of the free atom. H_a is assumed to arise from the unpaired outer s electron in the atom. We have investigated the contribution of the core electrons to H_a and in turn to the measured Knight shifts by means of spin (or exchange) polarized Hartree-Fock calculations. Several different atomic systems were considered: (1) K and Cu, which each have an outer unpaired $4s$ electron, and (2) Cr in the $3d^54s$ configuration. In (1) the polarized core contribution to H_a is positive (i.e., of the same sign as the $4s$ contribution) and a large fraction of the ordinary $4s$ contribution. In (2) the core polarization contribution is due to a competition between the unpaired $3d$ (which tend to produce a negative core contribution) and $4s$ electrons with the net hyperfine field being *negative*.

A8. NMR in the Intermetallic CaF_2 Structure. Unusual Ga Knight Shift in $AuGa_2$. V. Jaccarino, W. E. Blumberg, and J. H. Wernick, *Bell Telephone Laboratories, Inc.*—The Knight shifts of Pt, Al, Ga, and In in the intermetallic compounds $AuAl_2$, $AuGa_2$, $AuIn_2$, $PtAl_2$, $PtGa_2$, and $PtIn_2$, all possessing the isomorphic CaF_2 type structure, have been examined by NMR as a function of temperature from 4° to 300°K. Certain information concerning the metallic character of the two sites has been obtained. With the exception of $AuGa_2$ all Knight shifts are positive and exhibit a negligible temperature dependence. The Ga shift in $AuGa_2$, however, asymptotically approaches the values $k_{Ga}=+0.50\%$ at high temperatures ($T>450$°K) and -0.13% at low temperatures ($T<1.2$°K). The reversal of sign occurs at 68°K. The conductivities of $AuGa_2$ and $PtGa_2$ have been measured and exhibit no anomalous behavior between 4.2° and 300°K. This unusual behavior is examined from the point of view recently advanced[1] to explain negative Knight shifts in certain intermetallic compounds. The Pt shifts are the first ones reported for which $k_{Pt}>0$ (relative to the chloroplatinate ion in aqua regia). Contrary to the interpretation given originally by Rowland, it appears that the measured Knight shifts in Pt metal correspond to large negative values.

[1] A. M. Clogston and V. Jaccarino, Bull. Am. Phys. Soc. Ser. II, 5, 430 (1960); Phys. Rev. (to be published).

A9. Nuclear Magnetic Resonance in Intermetallic Compounds.* Harlan E. Schone† and W. D. Knight, *University of California, Berkeley.*—Nuclear magnetic resonance is observed in a series of intermetallic compounds of the type NaTl, including NaTl, LiAl, LiGa, and LiIn. Motional narrowing of the Li resonance line is observed in all compounds containing Li, the activation energy for the related diffusion process being 0.1 ev. The low activation energy is a result of the existence of a permanent concentration of vacancies in the "defect lattice." Motional averaging of quadrupole interactions is observed for the Li and Al lines in LiAl and their averaging temperatures are used to compute the magnitudes of first-order quadrupole interactions. Quadrupole couplings produced by a nearest-neighbor vacancy are 180 kc for Li^7 and 8.6 Mc for Al^{27}. Second-order broadening obliterates the Ga and In resonances in LiGa and LiIn below 200°K. From this behavior it can be estimated that the quadrupole couplings are of the order of or greater than 8 Mc for Ga^{71} and 30 Mc for In^{115}. Resonance shifts are approximately zero for all except the thallium, for which the shift is minus 0.5%.

* Supported in part by the U. S. Office of Naval Research.
† Present address: Boeing Scientific Research Laboratory, Seattle, Washington.

A10. Nuclear Magnetic Resonance Study of Electron Distribution around Solute Atoms in Silver-Base Solid Solutions. T. J. Rowland, *Union Carbide Metals Research Laboratories.*—It has been found that the change in the mean Knight shift of Ag^{109} upon alloying is proportional to solute concentration c and approximately proportional to the excess valence Z of the solute species. The absorption line width increases about as $c^{\frac{1}{2}}$ and Z, becoming 10 times greater than in pure Ag with the addition of 5 at.% solute in extreme cases. The major sources of the increase in width are the position dependence of the Knight shift and the indirect spin exchange of the Ag^{109} with the solute nuclei. The large increase in width accompanying small solute additions is ascribed to the long range of both the Fermi charge oscillations (introduced by the electronic structure of the solute) and the spatial oscillations in net spin caused by the presence of foreign nuclear moments. The theory of Blandin, Daniel, and Friedel[1] is used to interpret the line shifts and widths brought about by the displaced charge alone using phase shifts derived from (a) residual resistivity and Friedel sum rule, (b) square-well potential,[2] for several solute species.

[1] A. Blandin and E. Daniel, J. Phys. Chem. Solids 10, 126 (1959).
[2] F. J. Blatt, Phys. Rev. 108, 285 (1957); and correspondence.

A11. Nuclear Moment and Knight Shift of W^{183}.* Melvin P. Klein,† *Bell Telephone Laboratories, Inc.*, and James Happe, *Lawrence Radiation Laboratory, Livermore.*—Nuclear magnetic resonance in metallic tungsten was observed by Sogo and Jeffries.[1] However, unavailability of ionic solutions with sufficient concentration prevented observation of the tungsten resonance in a diamagnetic compound by conventional nuclear magnetic resonance techniques. We have observed the resonance of W^{183} in diamagnetic WF_6 by the nuclear-nuclear double resonance method.[2] The value of the nuclear moment thus obtained is $\mu(W^{183})=0.116205\pm0.000002$ nm. Application of a diamagnetic shielding correction of 0.87% gives a nuclear moment of 0.117216 nm. Comparison of this value with that obtained for metallic tungsten leads to a Knight shift of $+1.064\pm0.004\%$.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† On leave from the Lawrence Radiation Laboratory, Livermore, California.
[1] P. B. Sogo, and C. D. Jeffries, Phys. Rev. 98, 1316 (1955).
[2] V. Royden, Phys. Rev. 96, 543 (1954).

A12. Electric Field Gradient in Metallic Indium.* T. T. TAYLOR AND R. R. HEWITT, *University of California, Riverside.*—Following the observation of the nuclear quadrupole spectrum in metallic indium,[1] possible sources of the associated electric field gradient have been investigated. An ionic point charge sum has been calculated by a new method as a function of temperature from 0°K to the melting point of indium. The sum is in agreement with the values found independently by two other groups for room temperature.[2,3] In general, however, this ionic sum accounts for only about 20% of the observed field gradient. A simple electron density function, having the periodicity of the lattice, has been considered in terms of its ability to produce a field gradient in the amount required to obtain agreement with experiment. Such a model, characterized by a uniform density with a superposed sinusoidal fluctuation of about 25% relative magnitude, is sufficient to explain the observed gradient. The implications of this result will be discussed.

* Supported in part by the National Science Foundation.
[1] R. R. Hewitt and W. D. Knight, Phys. Rev. Letters **3**, 18 (1959).
[2] T. P. Das and M. Pomerantz, Bull. Am. Phys. Soc. Ser. II, **5**, 492 (1960).
[3] W. W. Simmons, Ph.D. dissertation, University of Illinois, Urbana, Illinois, 1960.

A13. Nuclear Quadrupole Resonance of Li in Ferroelectric Compounds. GERALD BURNS, *IBM Research Center, Yorktown Heights.*—The temperature dependence of the nuclear quadrupole coupling, eQq/h, of Li^7 in all known ferroelectrics containing Li has been measured to better understand these compounds. Most of the measurements were made using the powder method. However, for $LiNH_4$ tartrate (LAT) complete single-crystal data were taken in order to check explicitly the powder results. The agreement was found to be very good. For LAT, $eQq/h = 93$ kc/sec and $\eta = 0$ between -196°C and room temperature. There was no change through the transition temperature at -167°C. The results for LiTl tartrate were similar to -196°C. For the oxygen octrahedra compound, $LiTaO_3$, eQq/h was measured to $+325$°C. In this compound, the spontaneous polarization begins to increase at $\sim+200$°C and continues until $\sim+400$°C. $eQq/h = 81$ kc/sec at room temperature and increased $\sim 10\%$ at $+325$°C. The spontaneous polarization of $LiNbO_3$ behaves similarly to the Ta compound; below $+150$°C $eQq/h = 59$ kc/sec and was independent of temperature. The results for eQq/h of Li in the ferroelectric compounds $LiH_3(SeO_3)_2$ and $LiN_2H_5SO_4$ were less accurate because the asymmetry parameter η was not zero. However, changes in eQq/h and η can be measured. Thus, in some cases correlation between eQq/h and the ferroelectric properties can be seen and in other cases it cannot.

A14. Chlorine NQR in Paramagnetic $CuCl_2 \cdot 2H_2O$. W. A. ROBINSON, W. J. O'SULLIVAN, AND W. W. SIMMONS, *Space Technology Laboratories, Los Angeles.*—The Cl^{35} and Cl^{37} NQR have been observed with a superregenerative detector in powder and single-crystal samples of $CuCl_2 \cdot 2H_2O$ in the range 4.3°K to room temperature. The Cl^{35} resonance frequency is 9.05 Mc/sec, and the linewidth is approximately 35 kc/sec, appreciably broader than the resonances detected by Barnes and Segel[1] in the chlorides of V, Ti, and Cr. The experimental results are analyzed in terms of Moriya's[2] treatment of nuclear spin relaxation phenomena.

[1] R. G. Barnes and S. L. Segel, Phys. Rev. Letters **3**, 462 (1959).
[2] T. Moriya, Progr. Theoret. Phys. (Kyoto) **16**, 23, 641 (1956).

MONDAY MORNING AT 9:15

Criscuolo Hall

(H. Y. FAN presiding)

Semiconductor Junctions

B1. Simple Theory of Tunneling and Its Dependence on a Magnetic Field. P. N. ARGYRES AND B. LAX, *Lincoln Laboratory,** *M.I.T.*—A simple theory of tunneling between two parabolic bands is developed by a calculation of the transmission coefficient for an electron in the WKB approximation. The calculation of the tunneling current in a junction of any width is thereby possible. For a very broad junction and a constant electric field the (Zener) tunneling current is identical to that calculated more elaborately by Kane,[1] except for small differences in the numerical coefficients. For an Esaki diode the total tunneling current is found as a function of the applied voltage. The effect of a longitudinal magnetic field on the transmission coefficient is calculated quite simply. It is wholly accounted for by the shift of the band edges and the quantization of the transverse electronic energy due to the magnetic field. Esaki current is found to be reduced by the magnetic field. Small "oscillations" with the magnetic field are also predicted. The effect of a transverse magnetic field is more involved.

* Operated with support from the U. S. Army, Navy, and Air Force.
[1] E. O. Kane, J. Phys. Chem. Solids **12**, 181 (1959).

B2. On the Nature of the Excess Current in Tunnel Diodes.* T. P. BRODY, *Westinghouse Research Laboratories* (introduced by J. P. McKelvey).—An explanation of the "excess current" observed in tunnel diodes is suggested in terms of tunneling between impurity band states of the heavily doped p and n regions. Density-of-states curves are constructed, based on several different models of impurity bands, and the tunneling current between such bands is computed and compared with experiment. The effect of different base materials and impurities on the excess current is discussed in terms of the impurity band model. The possibility of obtaining information about impurity band structure from tunnel diode measurements is considered. The model also postulates Fermi levels which fall inside the intrinsic energy gap, despite the large degeneracy. Experimental evidence in favor of this aspect of the model is summarized.

* Work supported in part by U. S. Air Force, Wright Air Development Division.

B3. Electronic Processes in Gold-Doped Silicon Tunnel Diodes. C. T. SAH, *Fairchild Semiconductor Corporation.*—Electronic transitions in the space charge region involving two or more steps in which the intermediate state is one of the two gold levels are discussed. For gold-doped silicon tunnel diodes, eight transition routes are possible for which six have high probabilities. These are: (1) tunneling of a conduction electron horizontally to an acceptor gold level and subsequently emitted to the valence band by the neutral gold trap; (2)–(4) similar to (1) involving one of the two gold levels; (5) Hall-Shockley-Read recombination through the gold level;

(6), (7) two-step band-to-band tunneling horizontally with one of the two gold levels as intermediate state; (8) a three-step process involving (a) capture of a conduction electron by a neutral gold atom, (b) tunneling of this electron horizontally to an adjacent positively charged gold donor, and (c) emission of the electron by the gold donor to the valence band. Four of these processes have different and observable on-set voltages. Experimentally observed on-set voltages and negative resistance region at around 0.7 v at 4°K corresponding to turning-off of one of the processes (1)–(4) discussed are in good agreement with calculated values.

B4. Electron Bombardment Damage in Silicon Esaki Diodes.* R. A. LOGAN, W. M. AUGUSTYNIAK, AND J. F. GILBERT, *Bell Telephone Laboratories, Inc.* (introduced by G. Bemski).—Both the effects of bombardment and the properties of annealing of radiation damage in silicon Esaki diodes have been found to depend upon the specific donor in the n-type region of the diode. The average bombardment dose of 1-Mev electrons/cm^3 needed to increase the excess current density by 1 amp/cm^2 at a bias of 0.3 v is 1.2×10^{16} for P-doped diodes and 0.8×10^{16} for Sb- or As-doped diodes. The increase in excess current observed at room temperature is the same for bombardments at 78° or 300°K. Upon annealing in an inert atmosphere, at temperatures in the range of 300° to 400°C, the bombarded diode is restored to its original characteristics. The annealing kinetics for the As or Sb diodes are similar to those observed in As-doped Si in lifetime studies,[1] while the P-doped diodes anneal more rapidly. Structure observed in the I-V characteristic during the annealing will be discussed.

* This work was supported in part by the Wright Air Development Center of the U. S. Air Force.
[1] G. Bemski and W. M. Augustyniak, Phys. Rev. **108**, 645 (1957).

B5. Investigations of the Current-Voltage Characteristics of Germanium Esaki Diodes. MARSHALL I. NATHAN, *IBM Research Laboratories, Yorktown Heights.*—Simple tunneling theory predicts that $\ln(J/V)$ (J=current density, V=reverse bias) varies linearly with V for $eV\ll E_g$. Antimony-doped diodes which have phonon assisted current predominant at 4°K are found to exhibit such a dependence at room temperature for $V\lesssim0.1$ v. Moreover, in agreement with simple theory, the slopes S of the $\ln(J/V)$ plots for different diodes are proportional to $\ln J_p$ (peak current density) and hence[1] to the tunneling exponent θ. However, the constant of proportionality $\gamma(=\theta/S)$ is ~40% larger than the calculated value, if a constant field through the junction is assumed. It will be shown that, if the variations of field through junction is taken into account, such larger values of γ can be obtained. In arsenic doped diodes the onset voltage for tunneling to the (000) conduction band minimum[2] has also been observed as function of arsenic concentration up to 4×10^{19}/cm^3. It is found that the energy separation of the n-side (000) minimum and the Fermi level cannot be less, by more than 0.02 v, than the value expected on the basis of data obtained in pure material.

[1] S. L. Miller, M. I. Nathan, and A. C. Smith, Phys. Rev. Letters **4**, 60 (1960).
[2] J. V. Morgan and E. O. Kane, Phys. Rev. Letters **3**, 459 (1959).

B6. Slip Patterns on Boron-Doped Silicon Surfaces.* H. J. QUEISSER, *Shockley Transistor, Unit of Clevite Transistor.*—Diffusion of a high concentration of boron into a shallow surface layer of p- or n-type silicon slices and subsequent etching reveal regular arrays of etched lines with crystalline symmetries. These lines are interpreted as the traces of (111) slip planes. Slip is caused by the heavy deposit of substitutional boron atoms which leads to a reduction of the lattice parameter in the shallow surface layer. The dislocation arrays of the slipped regions extend much deeper into the material than one boron diffusion length. The high dislocation density thus introduced will affect the behavior of shallow p-n junctions.

* Research supported by the U. S. Air Force Cambridge Research Laboratories.

B7. Voltage Dependence of Microplasma Density in p-n Junctions in Silicon.* A. GOETZBERGER AND CHARLES STEPHENS, *Shockley Transistor, Unit of Clevite Transistor.*—The voltage distribution of breakdown spots in p-n junctions was measured. A junction in silicon which was uniform in its crystallographic properties showed two kinds of microplasmas. One type is characterized by light emission and low breakdown voltage, and the other has less light emission and higher breakdown voltage. Both have a rather broad distribution of breakdown voltages. Samples containing a grain boundary show only the first kind of microplasmas. The observed effects are in agreement with Shockley's SiO_2 precipitate model[1] of microplasmas.

* Research supported by the U. S. Air Force Cambridge Research Laboratories.
[1] W. Shockley, Solid State Electronics **2**, 35 (1961).

B8. Anodic Sectioning of Diffused Silicon p-n Junctions.* B. MCDONALD AND F. C. COLLINS, *Shockley Transistor, Unit of Clevite Transistor.*—The method described by Schmidt[1] for anodic oxidation of silicon is used to section a p-n junction for the purpose of studying the diffusion profile. Thickness of removed layers of silicon was determined by careful weighing on a microbalance and was found to be consistent on successive runs at constant current density. Diffused layers of 0.5-μ junction depth were sectioned in such a manner, conductivity measurements made after each sectioning, and from these the diffusion profile was studied. The results indicated that the impurity distribution did not follow the expected error function dependence.

* Research supported by the U. S. Air Force Cambridge Research Laboratories.
[1] Paul F. Schmidt, "Anodic oxide formation on silicon," in *Semiconductors and Phosphors*, Proceedings of the International Colloquium, 1956, at Garmisch Partenkirchen (Interscience Publishers, Inc., New York, 1958).

B9. Recombination Current in p-n Junctions and Distributions of Deathnium.* W. SHOCKLEY AND R. HENLEY, *Shockley Transistor, Unit of Clevite Transistor.*—In a silicon p-n junction at forward bias, the current is carried by recombination through deathnium centers in the space charge layer and varies with voltage V as $\exp(qV/AkT)$, where A changes from 1 at low forward bias to 2 at high forward bias. When A is 2, the recombination occurs chiefly through centers in a layer approximately $2kT/qF\approx10^{-6}$ cm wide, where F is the electric field. The location of this layer may shift with applied voltage. If the layer shifts to regions of lower deathnium density, the slope of log I vs V may become less than $q/2kT$ corresponding to A values greater than 2. These effects are relevant to the problem of solar cell efficiency.[1]

* Research supported by Wright Air Development Division.
[1] W. Shockley and H. J. Queisser, J. Appl. Phys. (to be published).

B10. Studies of Cleaved Germanium Surfaces.* S. ROY MORRISON, D. R. PALMER, AND C. E. DAUENBAUGH, *Honey-*

well Research Center.—The method of Statz and his co-workers[1] has been found particularly adaptable to electrical studies of clean (by cleavage) germanium surfaces. Earlier work[2,3] has shown that a strongly *p*-type surface layer is found on clean germanium. Our approach then has been to prepare by diffusion a *pnp* transistor-like structure, and cleave in such a way as to cleave through the junctions. Then biasing both junctions in the reverse direction, the "channel" resistance across the *p*-type surface layer is measured. The resistivity upon cleavage has turned out to be the order of 100 μmho/sq with an 0.1-v bias on the junctions. The resistivity variations with oxygen admission are similar to earlier work on argon-bombarded[2] and particularly cleaved[3] germanium surfaces. Analysis of the results will be discussed.

* Supported in part by U. S. Air Force Office of Scientific Research.

[1] H. Statz, G. A. DeMars, L. Davis, Jr., and A. Adams, Jr., *Semiconductor Surface Physics* (University of Pennsylvania Press, Philadelphia, Pennsylvania, 1957), p. 139.

[2] P. Handler, *Semiconductor Surface Physics* (University of Pennsylvania Press, Philadelphia, Pennsylvania, 1957), p. 23.

[3] D. R. Palmer, S. R. Morrison, and C. E. Dauenbaugh, J. Phys. Chem. Solids **14**, 27 (1960).

B11. Transient Photovoltaic Response of Diffused Junction Silicon Photodiodes. T. E. HARTMAN, *Texas Instruments Inc.*—The results of an experimental and theoretical study of the transient photovoltaic response of diffused junction silicon photodiodes will be presented. The analysis pertains to a thin *p*-type layer diffused in an *n*-type wafer illuminated on the *p*-type surface with intrinsic light. An exact solution for the transient response of the photocurrent at the junction shows that the rise time is limited by minority carrier storage. Expressions for the external photovoltage rise and fall times show that in general the rise time at room temperature with no external bias depends on the light intensity as well as the load resistance, while the fall time depends only on the load resistance. Previous[1,2] attempts by others to show experimental agreement with theory have not been completely satisfactory. Some of the experimental difficulties have been overcome by using an extremely fast light chopper.[3] Rise- and fall-time measurements made on 10 silicon photodiodes (TI type L*S*222) are in very good agreement with analysis. Impedance measurements which were important in showing the effect of load resistance on rise time will also be discussed.

[1] M. B. Prince and M. Wolf, J. Brit. Inst. Radio Engrs. **18**, 583 (1958).
[2] M. Becker and H. Y. Fan, Phys. Rev. **78**, 301 (1950).
[3] C. G. Peattie, W. J. Odom, and E. D. Jackson, Proc. Inst. Elec. Engrs. (London) **106**, Pt A, Suppl. No. 15 (1959).

B12. Hot and Cold Electron Diffusion. ROBERT STRATTON, *Texas Instruments Inc.*—The electron current in a semiconductor, at uniform lattice temperature T_0, under the influence of a nonuniform high electric field and an electron density gradient, consists of terms due to conduction, diffusion, and thermal diffusion. The first two terms involve the mobility and diffusion constant, each of which is a function of the electron temperature T; the third is due to the variation of T with position. T itself is not a unique function of the local field but also depends on the local density gradient. Equations for the determination of the first two terms in the spherical harmonic expansion of the distribution function are set up and their solution, under various approximations, will be discussed. As an example, computer solutions have been obtained for the volt-current characteristic of a Schottky-barrier metal-semiconductor contact assuming electron scattering due to acoustic phonons only. It turns out that T, in the barrier region, is greater than T_0 (i.e., hot electrons) for a bias applied in the reverse direction of the rectifier but less than T_0 (i.e., cold electrons) for a bias applied in the forward direction.

B13. *p-n* Junction Semiconductor Radiation Detector for Use with Beta- and Gamma-Ray Emitting Isotopes. NORMAN A. BAILY AND JAMES W. MAYER, *Hughes Aircraft Company.*—In order to use the *p-n* junction semiconductor as a detector for high-energy charged particles and for x and gamma rays, one has to increase the energy deposited within the charge sensitive region. This may be accomplished in two ways. First, increase the atomic number of the semiconductor material. Second, increase the depth of the charge sensitive region. We have chosen to attack this problem using the latter approach. Silicon has been successfully diffused with a lithium impurity, and by ion-drift techniques a sensitive volume has been established with a width of about 1 mm in comparison with the usual 10- to 100-μ width established when silicon is diffused with phosphorus.[1] Approximate sensitivities to gamma and beta rays will be given. On using Bi^{207}, both *K* and *L* levels are distinguished. By subtraction of the electron response the Compton edges may be observed.

[1] E. M. Pell, J. Appl. Phys. **31**, 291 (1960).

B14. Characteristics of Ion-Drifted Junction Detectors. JAMES W. MAYER AND HOWARD L. DUNLAP, *Hughes Aircraft Company.*—Ion-drifted junction detectors have been made by drifting lithium in *p*-type silicon following the technique of Pell.[1] Units have been fabricated from float-zoned and pulled material (1 to 30 ohm-cm) with active areas of 1 to 6 cm^2 having drifted regions up to 5 mm in depth. These depths have been verified by capacitance measurements, staining techniques, and the response to 30-Mev protons. Although capacitance vs voltage data indicate that the field extends substantially through the drifted region at bias voltages of approximately 10 v, higher voltages are required to obtain pulse rise times sufficiently fast (<0.1 μsec) for use in pulse-height analysis. Units have been fabricated which have shown no major change in *C* vs *V* characteristics over a one-month period. Fabrication techniques and the limitations inherent in drifted units will also be discussed.

[1] E. M. Pell, J. Appl. Phys. **31**, 291 (1960).

B15. Measurement of Damage in a Silicon Diffused Junction Fast-Neutron Dosimeter.* W. A. LINDGREN AND O. J. MENGALI, *Battelle Memorial Institute*, AND W. L. WEISS, *ANPD, General Electric Company.*—The equivalence of fast-neutron induced damage in silicon *p-n* junction dosimeters[1] to that in tissue was studied. Both monoenergetic neutrons and fission spectrum neutrons hardened by passage through water were used. The charge carrier lifetime of the device is sensitive to damage resulting from fast neutron irradiation. Annealing studies and calibration of the device with a standard flux have shown the characteristics to be reproducible within 5%. In its present state, the use of an individual device for dosimetry work depends upon calibration of its sensitivity to damage.

* This research was sponsored by the U. S. Atomic Energy Commission and the U. S. Air Force.

[1] Developed at Battelle for the U. S. Army Signal Corps under contract.

MONDAY MORNING AT 9:30

Ballroom, Herrman Hall

(F. HERMAN presiding)

Band Theory, X-Ray and Electron Scattering

Invited Paper

BA1. Effect of Exchange and Correlation on the Energy Band Structure. J. C. PHILIPS, *University of Chicago.* (30 min.)

Contributed Papers

BA2. Existence of Transition-Free Bands for a Crystal in a Homogeneous Electric Field. D. R. FREDKIN AND G. H. WANNIER, *Bell Telephone Laboratories, Inc.*—Suppose we deal with a one-particle Hamiltonian $\mathcal{H}$ which arises from the superposition of a periodic potential and a uniform electric field E. One can then construct a complete orthonormal set of states $B_\nu(x;k)$ having Bloch character with respect to the periodic potential; here k runs over a Brillouin zone and ν is a band index. These functions have the property that if the particle is initially in a particular band of index ν it will remain in the same band at all times. The functions $B_\nu(x;k)$ are the simultaneous eigenstates of the translation operators and the unitary, periodic operator $\exp[-i\mathcal{H}(2\pi/Ed)](\hbar=e=1)$. They are presumably the same functions as those previously introduced by one of the authors by means of power series; theorems 3, 4 and 5 of reference 1 are thus proved rigorously without reference to power series. However, contrary to the situation in reference 1, these theorems do not guarantee the existence of an in-band Hamiltonian. This is illustrated by exhibiting explicitly the $B_\nu(x;k)$ for free electrons, where, on physical grounds, the complete formalism of reference 1 cannot work. The crucial point here is that for free electrons $[B_\nu(k)\,|\,p^2\,|\,B_\nu(k)]$ is infinite. We do not know whether this result is relevant when a finite crystalline field is present.

[1] Gregory H. Wannier, Phys. Rev. **117**, 432 (1960).

BA3. One-Electron Energy Band Method. L. J. EYGES, *Lincoln Laboratory.**—We have tested a new method for the one-electron energy band problem i.e., for an electron bound to a periodic lattice. We start from the well-known equation for $C(\mathbf{K}_i)$, the Fourier coefficients of the wave function

$$C(\mathbf{K}_i) = -\Omega_b \frac{\sum C(\mathbf{K}_j) w(\mathbf{K}_i - \mathbf{K}_j)}{\{(\mathbf{K}_i+\mathbf{k})^2+\beta^2\}}.$$

We expand the $C(\mathbf{K}_i)$ in spherical (or Kubic) harmonics, and reduce the above equation to a set of coupled equations for the radial parts of the $C(\mathbf{K}_i)$ in reciprocal lattice space. This set of equations can be truncated to a good approximation, yielding a set of homogeneous equations relating the amplitudes $C(\mathbf{K}_i)$ evaluated at different absolute magnitudes of the reciprocal lattice points. We have tried solving these equations on a computer, so far for $\mathbf{k}=0$, and find that the energies and wave functions of low excited states can be found to very high accuracy. The present point of view also leads to a tight-binding method which has the advantage that all overlap integrals are effectively done at once, so that one does not have to rely on near-neighbor approximations.

* Operated with support from the U. S. Army, Navy, and Air Force.

BA4. Electronic Energy Bands in CsAu. VAN E. WOOD, *Battelle Memorial Institute* AND JOHN R. REITZ, *Case Institute of Technology.*—Valence and conduction electron energy bands in CsAu have been computed using the cellular method, with the radial parts of the wave functions determined by the quantum defect method. CsAu is assumed to be completely ionic. The results indicate that CsAu is a semiconductor, as found experimentally,[1] with a minimum energy gap, which is vertical, of about 2.3 ev located at the extremum of the ⟨111⟩ direction in the first zone.

[1] W. E. Spicer, A. H. Sommer, and J. G. White, Phys. Rev. **115**, 57 (1959).

BA5. Moment-Trace Method for Infinite Spectra. EVAN O. KANE, *Hughes Research Laboratory and Bell Telephone Laboratories, Inc.*—In generalizing the moment-trace method of Maradudin and Montroll[1] to infinite spectra, we first introduce a cutoff $|k| \gtrless Q_2$. We have the moment-trace indentities

$$\mathrm{Tr}(H_0+\lambda H_1)^n \equiv \mathrm{Tr}E^n. \tag{1}$$

λ is a perturbation expansion parameter. Assuming that the perturbation expansion of E defines an analytic function of λ with a finite radius of convergence, we obtain a series of identities from (1) by equating coefficients of equal powers of λ. We thus obtain the identity

$$\sum_{E=-\infty}^{E(Q_1)} E^n \equiv \sum_{k=0}^{Q_1} (E_p{}^n)_{\geq n} + \sum_{Q_1}^{Q_2} \{(E_p{}^n)_{\geq n} - E^n\}. \tag{2}$$

$(E_p{}^n)_{\geq n}$ means the perturbation expansion of E raised to the nth power carried to a *finite* order $\geq n$ in λ. We assume convergence for $|k| \geq Q_1$. It should be noted that (2) is both correct and useful even though E_p *diverges* for $k<Q_1$ for the values of λ of interest. We may now let Q_2 tend to infinity. The application of the method to the band structure of degenerate semiconductors will be considered.

[1] A. A. Maradudin, P. Mazur, E. W. Montroll, and G. H. Weiss, Revs. Modern Phys. **30**, 175 (1958).

BA6. Selection Rules Connecting Different Points in the Brillouin Zone. JOHN J. HOPFIELD AND MELVIN LAX, *Bell Telephone Laboratories, Inc.*—Selection rules for indirect radiative transitions and for intervalley scattering are investigated for Ge and Si. Comparison with experimental results of Haynes and of Aigrain supports (1) present picture of the band structure of Ge with a conduction band minimum at the zone boundary, (2) the assignment of L_3' as the symmetry of the LA phonon at the zone boundary in the 111 direction. The absence of the LA phonon in the Haynes radiative emission experiment still requires explanation. To obtain the required selection rules we take the product of two irreducible representations i and j that belong to *different* wave vectors k and k'. The resulting character product is expressed in a form appropriate to a third group $G_{k''}$ at $k''=k+k'$. If the elements of $G_{k''}$ are applied to k to generate a star and $N(C)$ is the number of points of the star invariant (or equivalent) under any element R in the class C (of $G_{k''}$) then the character product is $N(C)\langle\chi^i(R)\chi^j(R)\rangle_C$, i.e., $N(C)$ times the product of the

characters averaged over those R in C which belong to $G_{k'}$ and $G_{k''}$ (i.e., those whose characters can be found in the tables at k' and k'').

BA7. Time-Reversal Selection Rules with Application to Intervalley Scattering. MELVIN LAX, *Bell Telephone Laboratories, Inc.*—Whether a representation is real, pseudo-real, or complex, time reversal (TR) supplies additional selection rules for matrix elements between the representation and its TR representation (which is in the same space as the original, in a distinct but equivalent space, or an inequivalent space). If $\chi(R)$ is the character of the original representation, then the appropriate character product that determines the allowed symmetries in the Hermitian perturbation potential V is $\frac{1}{2}[\chi(R)]^2+\frac{1}{2}a\chi(R^2)$. If V is even under TR, then $a=1$ if spin is neglected. If spin is included, $a=\pm 1$ according as the number of electrons is even or odd. Each additional property: anti-Hermiticity, or oddness of V under TR, causes an additional sign change in a. These methods have been generalized to apply to selection rules connecting different points in the Brillouin zone. For intervalley scattering in Ge symmetry forbids X_2 and X_4, TR forbids X_3 leaving X_1, the degenerate LO, LA phonon as allowed. In Si scattering to an adjacent valley, symmetry forbids Σ_2 and Σ_3, TR forbids Σ_4, leaving Σ_1 a nondegenerate mixture of LA and TO polarized $\perp$ to the plane of the valleys. In Si scattering to an opposite valley, symmetry allows only $\Delta_1=LA$ and TR does, too.

BA8. "Forbidden" Reflection in Diamond,* LEONARD KLEINMAN AND JAMES C. PHILLIPS, *University of Chicago.*—The (222) x-ray scattering factor (F_{222}) for diamond, first measured accurately by Renninger,[1] is calculated from crystal wave functions previously obtained by the authors.[2] If the crystal charge density is represented by a superposition of charge densities spherically symmetric about each atomic site $F_{222}=0$ because the corresponding structure factor vanishes; however Renninger's experimental value is 0.14. A crude tight-binding calculation of Ewald and Hönl[3] gave the value 0.03, while the present band calculation yields $F_{222}=0.09\pm 0.02$, in substantially better agreement with the experimental value. We have also calculated F_{111}, F_{220}, and F_{311} and compared them with Brill's[4] experimental values and his heuristic picture of the charge density in diamond.

* Supported in part by the Office of Naval Research.
[1] M. Renninger, Acta Cryst. **8**, 606 (1955).
[2] L. Kleinman and J. C. Phillips, Phys. Rev. **116**, 880 (1959).
[3] P. P. Ewald and H. Hönl, Ann. Physik **26**, 673 (1936).
[4] R. Brill, Z. Elektrochem. **63**, 1088 (1959).

BA9. Effect of Temperature on Diffraction of X Rays from "Perfect" Crystals. BORIS W. BATTERMAN, *Bell Telephone Laboratories, Inc.*—Thermal motion can be considered an imperfection in an otherwise perfect lattice. It is well known that the integrated intensity of a Bragg reflection from a "perfect" crystal is significantly smaller than from one ideally imperfect. Thus, from an imperfection point of view, it might be expected that thermal motion should increase the integrated intensity of a perfect crystal Bragg reflection, while according to the usually accepted treatment, which has not been experimentally verified, the intensity should decrease according to the Debye-Waller factor, $\exp(-M)$, for amplitudes. Using a double-crystal spectrometer, we have measured the integrated intensity of the (555) reflection from a "perfect" silicon single crystal with Mo$k\alpha$ radiation at temperatures ranging from 289° to 698°K and find a decrease in intensity with increasing temperature in qualitative agreement with theory. The reduction in intensity from the lowest to the highest temperature is somewhat greater than one would calculate from an approximate Debye-Waller treatment using a Debye temperature of 650°K.

BA10. X-Ray Spectrometric Properties of Natural and Synthetic Quartz. E. L. JOSSEM AND P. C. CLASPY, *The Ohio State University.**—The x-ray spectrometric properties of natural and synthetic quartz have been investigated in connection with the problem of making corrections for instrumental resolving power in precision x-ray spectrometry and x-ray wavelength determinations. It has been found that samples of synthetic quartz have spectrometric properties which put them in a class with the best natural quartz crystals. One is thus released from dependence on accidents of nature in obtaining satisfactory crystals for high resolution spectrometry. It has also been established that the criteria usually employed in two-crystal x-ray spectrometry for the selection and characterization of crystals of high resolving power [e.g., (1, −1) and (1, +1) rocking curve widths and percent reflection] are inadequate and that one must determine the shape of the entire diffraction pattern including the remote tail region. The diffraction patterns are sensitive to the nature and method of preparation of the crystal surface. In many crystals, both natural and synthetic, the diffraction patterns may undergo relatively large and relatively rapid changes with time. The role of x radiation in such changes has been examined and is believed to be confined to possible secondary effects.

* Supported in part by the Office of Naval Research.

BA11. Theory of Bremsstrahlung from Crystals. P. R. AUVIL, JR., AND L. I. SCHIFF, *Stanford University.*—Recent experiments on the bremsstrahlung from high-energy electrons traversing a silicon single crystal[1] show a minimum at zero value of the angle between the electron beam and the crystal axis. This minimum is predicted by a theory[2] which assumes the validity of the Born approximation; however, in one of the experimental situations (small photon energy), breakdown of the Born approximation is expected[3] to wash out the minimum. A more careful analysis has now been made, which first, shows that the range of validity of the Born approximation increases when the angle between electron beam and crystal axis deviates from zero, and second, gives an improved criterion for the washing-out of the central minimum. It now seems possible that the theory is consistent with the observations[1] for small photon energy.

[1] G. Bologna, G. Diambrini, and G. P. Murtas, Phys. Rev. Letters **4**, 572 (1960).
[2] H. Überall, Phys. Rev. **103**, 1055 (1956).
[3] L. I. Schiff, Phys. Rev. **117**, 1394 (1960), Sec. II.

BA12. Scattering of 50-kv Electrons at Very Small Angles.* BENJAMIN M. SIEGEL AND LUIS BACHMANN,† *Cornell University.*—The differential scattering cross-section of 50-kv electrons from carbon and copper has been measured in the angular range of 1 to 5×10^{-3} radians. Using the optics of the electron microscope and monitoring the incident intensity with a Faraday cage, absolute values have been obtained and compared with the theoretical curves given by Lenz.[1] Good agreement is obtained for carbon if the screening radius of the potential field of the nucleus used by Leisegang[2] is chosen. The measured values of the scattering cross section obtained for copper are larger by a factor of 2 than the calculated values.

* Supported in part by the U. S. Air Force Office of Scientific Research and the Advanced Research Projects Agency.
† Now at the Physikal Chemical Institute, University of Innsbruck, Austria.
[1] F. Lenz, Z. Naturforsch. **9a**, 185 (1954).
[2] S. Leisegang, Z. Physik **132**, 183 (1952).

MONDAY MORNING AT 9:30

Copper Cup Room, Herrmann Hall

(L. O. OLSEN presiding)

Photo Effects

C1. Temperature Dependence of Anomalous Photovoltages in ZnS. G. CHEROFF, *IBM Research Center, Yorktown Heights.*—Attempts to explain photovoltages, larger than band gap, in ZnS[1] and other materials[2] have invoked the use of barrierlike mechanisms occurring at stacking faults or at transition regions between hexagonal and cubic phases. Temperature measurements by Merz[1] of the effect indicated that this behavior is predicted by simple *p-n* junction theory. We have made measurements of the wavelength dependences of the open circuit photovoltages and short circuit photocurrents at various temperatures in the range between 77° and 580°K. The open circuit voltage increased in general below room temperature, but in some samples was found to reach a minimum at about 430°K and then became larger with increasing temperature. The short circuit photocurrents uniformly increased with increasing temperature. The data indicate that a simple *p-n* junction mechanism is not valid.

[1] W. J. Merz, Helv. Phys. Acta **31**, 6 (1958).
[2] L. Pensak, Phys. Rev. **109**, 601 (1958); B. Goldstein, *ibid.* **109**, 601 (1958).

C2. Origin of Anomolous Photovoltaic Effect in ZnS and CdTe. A. R. HUTSON, *Bell Telephone Laboratories, Inc.*—Anomolously high-photovoltaic effects have been observed on stack-faulted crystals of ZnS[1] and evaporated polycrystalline films of CdTe.[2] Previous attempts to explain these effects have postulated *p-n* junctions or barriers but have given no satisfactory explanation of their origin or the fact that their individual photovoltages must add in series. The present model proposes that the barriers are produced piezoelectrically by strain gradients occuring at the stack faults and grain boundaries. The strain in ZnS is postulated to arise from a slight difference between the cubic and hexagonal lattice constants perpendicular to the *c* axis. Hence the barrier fields are produced in one direction in the cubic material and the opposite direction in the hexagonal material. Selective absorption of light can then determine photovoltage sign. The strain in the CdTe films probably arises from differential expansion with respect to the substrate and is localized in necks between grains in which the fields will have the same direction to within the degree of crystal orientation of the film.

[1] S. G. Ellis, F. Herman, E. E. Loebner, W. J. Merz, C. W. Struck, and J. G. White, Phys. Rev. **109**, 1860(L) (1958).
[2] L. Pensak, B. Goldstein, Phys. Rev. **109**, 601 (1958).

C3. Recombination Time, Mobility, and Trap Concentrations in Cu:Cl-Doped CdSe. S. TRIEBWASSER AND G. CHEROFF, *IBM Research Center, Yorktown Heights.*—A combination of dynamic relaxation and steady state measurements of photosensitivity have been made on sintered layers of CdSe over a wide range of Cu doping levels. Analysis of both photoconductivity decay curves, as well as response to sinusoidal light variation measured as a function of frequency and background light level, yields values of mobility and recombination lifetime as well as trap densities.[1] It is found that over the doping range of 0 to 1000 ppm Cu, the recombination time varies in a highly nonlinear manner from 2 msec to 20 μsec. To first order, the electron mobility is independent of light level (0–500 $\mu w/cm^2$) and doping level with values in the vicinity of 100 cm^2/vsec being observed. Qualitatively, it is observed that electron trap densities decrease with increased Cu concentration.

[1] For discussion of the relations used in these analyses, see I. Broser and R. Broser—Warminsky, Ann. Physik **16**, 361 (1955), and E. A. Niekisch, *ibid.* **15**, 279 (1955); *ibid.* p. 288.

C4. Photoconductivity of GaAs:Si:Cu Crystals.* RICHARD H. BUBE AND JOSEPH BLANC, *RCA Laboratories.*—High-resistivity crystals of GaAs:Si:Cu have been prepared with high photosensitivity at low temperatures by diffusing copper into low-resistivity *n*-type GaAs:Si crystals. Such crystals show *p*-type conductivity at room temperature; in order for photosensitivity to be present at low temperatures, the room temperature dark conductivity must not exceed 5×10^{-6} mho/cm. This limitation is incurred by the fact that photosensitivity is associated with the presence of compensated acceptor levels lying 0.42 ev above the valence band, which act as sensitizing centers for *n*-type photoconductivity. These levels capture photo-excited holes and have a subsequent cross section for electron capture 6×10^3 times smaller than their initial cross section for hole capture. Such crystals have an effective spectral range from about 0.8 to 1.1 μ, a specific sensitivity equal to or slightly exceeding that of standard photosensitive CdS, and a speed of response at 90°K which exceeds that of standard CdS at room temperature. Trap densities governing the speed of response are of the order of 10^{14} cm^{-3}. The 0.42-ev level is detected by measurement of *p*-type conductivity vs temperature, and by thermal and optical quenching of photoconductivity.

* Sponsored by the Air Research and Development Command, U. S. Air Force.

C5. Optical Absorption Spectra of Impurity Ions of the First Transition Series in ZnS. R. E. DIETZ AND R. PAPPALARDO, *Bell Telephone Laboratories, Inc.*—The optical absorption spectra of single crystals of ZnS doped by diffusion with ions of the first transition series were studied in the region of 4 to 0.3 μ at room temperature, 78° and 4.2°K. By comparing the observed spectra with that predicted by the crystal field theory, the ionic charge and site symmetry of Cu, Ni, Co, Fe, Mn, and Cr impurities were found to be consistent with the respective divalent ion in tetrahedral coordination. Vanadium is probably present in the trivalent state, while the spectrum of Ti is not well understood. In some samples containing Cu, absorptions other than those associated with the divalent ions are observed, suggesting the presence of more than one valence state. The empirical values of the parameters Dq, B, and C for the various ions in ZnS are in good agreement with those observed for CdS.[1] The absorption spectra of Cu, Mn, and V agree very well with the fluorescence excitation spectra reported by other workers for phosphor powders of ZnS, both with respect to energies and relative intensities of the various bands. However, the emissions reported for these phosphors do not appear to correspond to crystal field transitions within the impurity ion.

[1] R. E. Dietz and R. Pappalardo, Bull. Am. Phys. Soc. **5**, 416 (1960).

C6. CdS in the Near Infrared under Electron Bombardment. BERNARD A. KULP, *Aeronautical Research Laboratory.*—In certain platelet type single crystals of CdS of the order of 100 μ in thickness grown by Reynolds and Greene of this laboratory, there appear fluorescence bands at 8600 and

10 500 A when the crystals are bombarded with 300-kev electrons at room temperature. The intensity of the 10 500 A band is almost independent of electron beam current in the range 0.5 to 5 $\mu a/cm^2$. The intensity of the 8600-A band varies approximately linearly with the intensity of the electron beam in the same current range. Both bands decrease in intensity by a factor of about 5 (in several crystals) when the temperature is lowered to −195°C. The 8600-A band is removed from these platelets by bombardment at 300 kev at a level of 5 $\mu a/cm^2$ for a period of 10 to 50 hr depending on the initial intensity of the fluorescence. This represents 5×10^{17} to 2.5×10^{18} electrons/cm^2 striking the crystal. The 10 500-A fluorescence is not affected by this bombardment. The crystal resistivity increases as the fluorescence is removed. However the fluorescence is no longer detectable no further change in resistivity is observed. The total change in resistivity before and after removal of the fluorescence is dependent upon the initial intensity of the fluorescence band. The origin of the 8600-A fluorescence band is being investigated but to date chemical analysis has been uncertain as what impurity is responsible for it.

C7. Effect of Pressure on the Emission and Reflection Spectra in Cadmium Sulfide. D. W. Langer and W. R. Lauterbach, *Aeronautical Research Laboratory* (introduced by Lee Devol).—Measurements were made on the pressure dependence of two phenomena closely related to the band gap in CdS. The blue lines with peaks at $B_0-2.558$, $B_1-2.542$, and $B_2-2.512$ ev emitted by CdS while at 77°K and under ultraviolet stimulation shift with pressure linearly up to 9000 bars with a pressure coefficient of $+4.6\times10^{-6}$ ev/bar. Since B_1 is taken to be the conduction—Γ_9 valence band transition,[1] B_0 is considered to be the conduction—upper Γ_7 valence band transition. The structure in the reflection spectrum of CdS at 77°K is probably due to transitions from the three valence bands to an exciton level[2] represented by the peaks at *A*-2.544, *B*-2.559, and *C*-2.616 ev. Their shift over this same pressure range was found to be linear with a pressure coefficient of 4.5×10^{-6} ev/bar. The agreement of these values with the pressure coefficients of the absorption edge and green emission[3] is good. No change of the spin-orbit splitting nor the crystal field splitting of the valence band was detected since *A*, *B*, and *C* have the same pressure coefficient.

[1] L. S. Pedrotti and D. C. Reynolds, Phys. Rev. **120**, 1664 (1960).
[2] D. Thomas and J. Hopfield, Phys. Rev. **116**, 573 (1959).
[3] D. W. Langer, International Conference on Semiconductor Physic, Prague, 1960.

C8. Edge Emission in ZnSe Crystals at Low Temperatures. O. W. Larson and L. S. Pedrotti, *Air Force Institute of Technology* and D. C. Reynolds, *Aeronautical Research Laboratory* (introduced by C. W. Litton).—Fluorescence near the fundamental absorption edge in ZnSe single crystals has been investigated at 77° and 4.2°K. The ZnSe crystals, about 0.2 mm thick, were grown from the vapor phase.[1] At both 4.2 and 77°K the crystals were irradiated with ultraviolet light and the fluorescence was photographed with the Bausch & Lomb two-meter grating spectrograph. The structure of the emission at 4.2°K contains a series of lines and three broad bands. The lines. located just to the long wavelength side of the absorption edge, have wavelengths of 4420, 4449, 4497, 4550, 4602, and 4653 A. The last five lines have a separation energy approximately equal to the measured value of the phonon energy, 0.027 ev.[2] The three broad bands, varying in width from 500 to 1000 A are centered near 4950, 5350, and 6110 A. At 77°K the intensity of the fluorescence is reduced and the structure is changed. Two lines, less intense, are found near the absorption edge, one at 4421 A and one at 4435 A. The three broad bands are less intense and somewhat more diffused.

[1] L. C. Greene, *et al.*, J. Chem. Phys. **29**, 1375 (1958).
[2] D. T. F. Marple, *et al.* (to be published).

C9. Spin-Orbit Splitting in ZnCd:S Single Crystals. D. C. Reynolds and C. W. Litton, *Aeronautical Research Laboratory*.—The spin-orbit splitting has been measured in both CdS[1] and ZnS[2] yielding values of 0.016 and 0.026 ev, respectively. These values were obtained at liquid N_2 temperature. Single ZnCd:S crystals have been grown from the vapor phase and an approximately linear relationship between band gap and anion concentration was reported.[3] Spin-orbit splitting *s* have been determined from reflection measurements on crystals containing up to 20% Zn in CdS and on crystals containing up to 7% Cd in ZnS. Spin-orbit splittings have not as yet been observed in crystals containing higher concentrations than those mentioned above. It is believed that inhomogenieties in the higher concentrations cause an energy spread in the band edges over finite distances in the crystal and the reflection peaks are "washed" out. The spin orbit splittings in the mixed crystals vary nonlinearly between the values observed in CdS and those obtained in ZnS. These variations will be reported.

[1] D. G. Thomas and J. J. Hopfield, Phys. Rev. **116**, 573 (1959).
[2] A. Lempicki, *et al.*, International Conference on Semiconductor Physics, Prague, 1960.
[3] L. C. Greene and D. L. Kingston, Bull. Am. Phys. Soc. **4**, 157 (1959).

C10. Field-Induced Emission in CdS Crystals Exhibiting Mechanically Excited Emission. C. W. Litton and D. C. Reynolds, *Aeronautical Research Laboratory*.—Ultraviolet stimulated emission in crystals that exhibit mechanically excited emission differs from crystals that do not in that the first broad green line is less intense than the second. The center responsible for this emission is the sulfur interstitial atom.[1] The second and succeeding lines are believed to be due to phonon interaction. Many of these crystals show high resistance in the dark and at liquid N_2 temperature. In this condition fields of several kilovolts per cm can be applied with no observable emission. When the crystal is exposed to light the conductivity increases by many orders of magnitude and the high conductivity remains even after the light is removed.[2] In this state fields of the order of 10 v/cm result in relatively intense emission. The spectral distribution of this emission is identical with the uv excited emission from the same crystal. The emission is believed to result from carrier injection. This is made possible by filling the hole traps while the crystal is exposed to light and can be explained on the basis of the model[2] proposed for mechanically excited emission.

[1] B. A. Kulp and R. H. Kelley, J. Appl. Phys. **31**, 1057 (1960).
[2] D. M. Warschauer and D. C. Reynolds, J. Phys. Chem. Solids **13**, 251 (1960).

C11. Recombination Coefficients of CaO Lumophors for Nitrogen Atoms.* K. M. Sancier, J. L. Hatchett, W. J. Fredericks, and H. Wise, *Stanford Research Institute*.—A lumophor such as CaO may be made to luminesce when nitrogen atoms recombine heterogeneously on its surface.[1] Simultaneously some of the energy released in the recombination process appears as thermal energy of the solid. Experimentally, the quantity of heat released and the intensity of luminescence produced in the heterogeneous recombination were measured as a function of distance from the atom source, an electrodeless, rf discharge in dry nitrogen. From these measurements the recombination coefficients for heat and light production (γ^H,γ^L) were evaluated.[2] For pure CaO the values of γ^H and γ^L were found to be different. Activation of CaO with manganese produced a second luminescence band at longer wave length with $\gamma_{CaO:Mn}{}^L$ different from $\gamma_{CaO}{}^L$. These results suggest different mechanisms of recombination-energy transfer and conversion in the production of luminescence and heat.

* Supported by the U. S. Air Force, Office of Scientific Research.
[1] K. M. Sancier, W. J. Fredericks, and H. Wise, J. Chem. Phys. **30**, 1355 (1959).
[2] H. Wise and C. M. Ablow, J. Chem. Phys. **29**, 634 (1958).

C12. Diffuse Reflectance of Powders. NATHAN T. MELAMED, *Westinghouse Research Laboratories.*—An equation is derived which relates the reflectance of powders to the optical absorption coefficients of the bulk materials, their indexes of refraction and their particle size. Use of the equation permits the determination of absolute optical absorption coefficients with good accuracy on materials which are not readily available in a form suitable for direct transmission measurements. In addition, the equations permit the calculation of a number of properties of luminescent powders, e.g., quantum yields in the presence of self-absorption.

C13. Far-Infrared Interference-Modulation Spectrometer.* A. S. BAKER, JR., AND M. TINKHAM, *University of California, Berkeley.*—A spectrometer of the path length modulation type[1] has been constructed and used for transmission and reflection measurements in the region 80 to 1000 μ. A linear lift cam gives an oscillating motion to alternate facets of an interleaved set of strip mirrors. When the cam is at the minimum excursion position all the mirror surfaces are parallel and flush forming a smooth reflecting surface. A collimated beam from the source is directed on the mirrors. Upon mixing the beams reflected from the stationary and moving mirrors, the radiation of wavelength λ appears amplitude modulated at frequency $4\Delta f_0/\lambda$ where f_0 is the frequency and Δ the amplitude of the mirror motion. Several narrow-band amplifiers operating at different frequencies after the detector permit observation of several wavelengths simultaneously.

* Supported in part by the Office of Naval Research, the National Science Foundation, and the Alfred P. Sloan Foundation.

[1] L. Genzel and R. Weber, Z. angew. Phys. **10**, 127 (1958).

C14. Production of Pairs in Semiconductors by Low-Energy Electrons. W. E. SPICER, *RCA Laboratories, Princeton.*—Using the velocity distribution of photoelectrons, the probability for pair production[1] has been studied in a number of alkali-antimonide semiconductors[2] as a function of electron energy. Electrons with energies ranging between 0.5 and 6.0 ev have been used. The threshold energy for pair production is found to range from over three times the band gap in Na_2KSb to one or two times the band gap in Cs_3Sb. The band gaps of all these materials studied lie between 1.0 and 1.6 ev. Through a detailed analysis of the velocity distribution, it is possible to obtain a measure of the mean free path for pair production as a function of electron energy. This varies from several hundred angstroms for electrons with energies a few tenths of an electron volt above the threshold energy to about 10 A for electrons with energies about one electron volt in excess of the threshold energy.

[1] L. Apker and E. Taft, J. Opt. Soc. Am. **43**, 78 (1953).
[2] W. E. Spicer, Phys. Rev. **112**, 114 (1958); J. Appl. Phys. **31**, 2077 (1960).

MONDAY MORNING AT 9:30

King Hall

(R. J. ELLIOT presiding)

DSSP Symposium on Magnetism of Rare Earths and Compounds

CA1. Spiral Spin Configuration. T. A. KAPLAN, *Brookhaven National Laboratory.* (30 min.)

CA2. Magnetic Ordering in Rare Earth Metals and Compounds. M. K. WILKINSON, *Oak Ridge National Laboratory.* (30 min.)

CA3. Cooperative Phenomena from the Single Ion Viewpoint: Ytterbium Iron Garnet. R. L. WHITE, *Hughes Research Laboratory.* (30 min.)

CA4. Calorimetric Determination of Energy Levels in Rare Earth Garnets. H. MEYER, *Duke University.* (30 min.)

MONDAY MORNING AT 9:30

400 Spanagel Hall

(G. FEHER presiding)

Color Centers

D1. Paramagnetic Resonance of *F* Centers in Alkali Halides.* WILLIAM C. HOLTON† AND HAYWOOD BLUM, *University of Illinois.*—The hyperfine coupling of the *F* electron to nuclei neighboring the negative ion vacancy has been measured by electron-nuclear double resonance for *F* centers in NaCl, LiCl, NaF, and LiF. Root second moments of the resonance absorption, obtained from slow passage, agree with values calculated from the hyperfine constants. These experimental results, together with those of previous workers, are compared with the Gourary and Adrian (G&A) theory.[1] The G&A expression, $|\phi(\alpha)|^2 = A_\alpha |\psi(\alpha)|^2$, relates the electron density at the α nucleus to the product of an *F*-electron envelope function $[\psi(\alpha)]$ with an amplifying factor (A_α). As stated by G&A, A_α is shown to be dependent only on the electronic structure of the α ion. The functional dependence of A on the atomic number (Z) is found to be, $A \propto Z^3$.

* Supported jointly by the U. S. Atomic Energy Commission and an Alfred P. Sloan Grant to C. P. Slichter.

† Present address: Texas Instruments Inc., Dallas, Texas.

[1] B. S. Gourary and F. J. Adrian, in *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic Press, Inc., New York, 1960), Vol. 10, p. 127.

D2. Paramagnetic Resonance of *F* Centers in LiF. HAYWOOD BLUM,* *University of Illinois,* AND WILLIAM C. HOLTON, *Texas Instruments Inc.*—We have studied the electron spin resonance (ESR) of x-rayed LiF crystals. The resonance exhibits partially resolved structure which depends on the crystal orientation in the magnetic field (H_0). For the [100], [110], and [111] directions parallel to H_0, there are ~35

partially resolved lines with spacings of 14.3, 12.1, and 14.7 gauss, respectively. At 72° from the [001] direction in a [110] plane, there are over 70 lines with a spacing of 6.75 gauss. Kim *et al.* have observed the same ESR structure pattern, and suggest that it is not due to the *F* center.[1] However, using previously obtained electron-nuclear double resonance data for the *F* center in LiF,[2] the detailed *F*-center ESR line shape for the [111] and 72° directions has been calculated on an IBM 704 computer; the computer and experimental results agree to within 3%. Thus, we believe the structure is due to the *F* center as originally proposed.[2]

* Supported jointly by the U. S. Atomic Energy Commission and an Alfred P. Sloan Grant to C. P. Slichter.
[1] Y. W. Kim, R. Kaplan, and P. J. Bray, Phys. Rev. Letters 6, 4 (1961).
[2] W. C. Holton, H. Blum, and C. P. Slichter, Phys. Rev. Letters 5, 197 (1960).

D3. Optical Absorption and EPR after Optical Bleaching of *F* Centers. W. E. Bron and R. S. Title, *IBM Research Center.*—X-rayed crystals of KCl were optically bleached at room temperature to produce *R*, *M*, and *N* centers at the expense of *F* centers. This produces a marked shift of the high-energy side of the *F* band, such that its half-width at 80°K increases from 0.197 to 0.232 ev, and also decreases the width of the room temperature EPR line from 45 to 34 gauss. When the sample is heated for a short period at 140°C in order to remove all *R* centers, the half-width of the *F* band decreases to near 0.200 ev and the width of the EPR line returns to 45 gauss. The half-width of the *F* band decreases to the original value of 0.197 ev after additional thermal treatment at 140°C to remove *M* and *N* centers. The broadening of the *F* band and the decrease in the width of the EPR line, therefore, appear to result primarily from the presence of *R* centers. These results also show that *F* centers are still present after prolonged optical bleaching and suggest that the *R* center is paramagnetic, but *M* and *N* centers are not.

D4. Radiation Damage in Crystalline Fluorides.* Charles D. Knutson, R. Kaplan, and P. J. Bray, *Brown University.*—Neutron-irradiated crystalline fluorides have been investigated using the techniques of nuclear magnetic resonance (NMR) and electron-spin paramagnetic resonance (ESPR). Measurements previously reported[1,2] on LiF have been extended to include CaF_2 and NaF single crystals. Under certain conditions it has been found that pile irradiation produces colloidal metal and molecular fluorine within the lattices of these materials. NMR measurements of the gaseous fluorine in all three compounds yield the fractions of these materials present in the lattice after irradiation. Information concerning the configuration of the colloidal sodium in irradiated NaF has been obtained both from NMR measurements and from observation of the ESPR of conduction electrons in the sodium metal. Irradiated crystals of BaF_2 and KF are being investigated.

* Research supported by the U. S. Atomic Energy Commission.
[1] P. J. Ring, J. G. O'Keefe, and P. J. Bray, Phys. Rev. Letters 1, 1508 (1958).
[2] Y. W. Kim, R. Kaplan, and P. J. Bray, Phys. Rev. 117, 740 (1960).

D5. Role of Dislocations in the Formation of *F* Centers by X Irradiation.* C. L. Bauer and R. B. Gordon, *Yale University.*—Internal friction and elastic modulus experiments suggest *F* centers are formed at dislocations during x-irradiation even at liquid-helium temperature, but enhanced colorability is suppressed at low temperatures by lack of diffusion. *F*-center growth curves were made in plastically deformed (up to 14%) NaCl and KCl at temperatures ranging from 78° to 325°K. The rate of formation of *F* centers can be explained using the two-stage growth model. Colorability of lightly deformed crystals is only enhanced at temperatures where diffusion of *F* centers is possible; a rapid saturation of this deformation sensitive coloration is observed at lower temperatures. The initial growth rate in a heavily deformed crystal, relative to an undeformed one, becomes larger as the temperature is decreased, and can be explained by the presence of a large number of *F* centers formed near dislocations. With further x irradiation, this additional contribution saturates. Substantiating the hypothesis that the additional growth is due to *F*-center formation near dislocations, and that diffusion is necessary for growth to continue, a distinct broadening of the *F* band is observed which disappears when the crystal is warmed to room temperature.

* Supported by the National Science Foundation.

D6. Low-Temperature Dislocation Damping in the Alkali Halides.* R. B. Gordon and C. L. Bauer, *Yale University.*—Changes in the damping and elastic modulus of plastically deformed rock salt, due to dislocation pinning, have been observed during x irradiation at liquid-helium temperature and during subsequent warmup. The rate at which these changes occur during irradiation at helium temperature is comparable to that at higher temperatures, but the magnitude of the effect is smaller. The decrease in magnitude has been shown to be due to the absence of thermal unpinning. The low-temperature dislocation pinning in NaCl, KCl, KBr, and KI is found to be reversible when the crystals are subjected to illumination in, or near, the visible. The wavelength of the illumination which produces the maximum unpinning increases with increasing lattice constant; the effect disappears when the crystals are warmed to room temperature. The pinning point is tentatively identified as a jog in close association with an *F* center whose absorption band is displaced by the dislocation strain field. Ionization of the *F* center results in recombination of its vacancy with the jog; warmup allows the *F* center to diffuse beyond recombination range.

* Supported by the Office of Naval Research.

D7. Paramagnetic Resonance Investigation of Atomic Hydrogen and Tritium in Neutron-Irradiated Crystalline Fluorides.* J. A. Dweck and P. J. Bray, *Brown University.*—The electron-spin paramagnetic resonances of atomic hydrogen and tritium have been observed at room temperature in neutron-irradiated crystalline fluorides. In LiF, tritium is a product of the disintegration of Li^6 nuclei via the reaction $Li^6(n,\alpha)H^3$. The atomic hydrogen presumably results from the breakup of OH radicals present in the crystals. The observed electron spin resonance doublets may be identified by their characteristic g value and splittings of 543.2 ± 0.1 and 508.6 ± 0.1 gauss for tritium and hydrogen, respectively. Both have linewidths of about 2 gauss. From the structure of the individual hyperfine components some insight into the positions of the hydrogen and tritium atoms in the lattice and their interactions with the neighboring lattice atoms may be gained. The dependence of the spectra on post-irradiation thermal treatment will be considered.

* Research supported by the U. S. Atomic Energy Commission.

D8. X-Ray Induced Defects in LiF Crystals Plastically Deformed at Low Temperatures.* D. A. Wiegand, *Carnegie Institute of Technology,* and R. Smoluchowski, *Princeton University.*—LiF crystals have been deformed in compression at liquid-nitrogen temperature and x-ray irradiated without intermediate warming. Both the *F* band and *a* band in the vicinity of 3400 A are enhanced as a result of the deformation, and the fractional increase in the *F* band is proportional to the fractional increase of the 3400 A band. While the *F* band continues to grow throughout the period of irradiation, Δn_f due to deformation saturates in a very similar fashion to the band at 3400 A. These results can be interpreted very simply in terms of vacancy generation during deformation, the negative ion vacancies being readily converted to *F* centers during irradia-

tion. The saturation of Δn_f suggests that the rate of formation of negative ion vacancies during irradiation is insensitive to this plastic deformation as reported earlier for crystals deformed at room temperature.[1]

* Supported by the U. S. Atomic Energy Commission.
[1] D. A. Wiegand and R. Smoluchowski, Bull. Am. Phys. Soc. 4, 148 (1959).

D9. Stored Energy in X-Irradiated Sodium Chloride.* FRED T. PHELPS AND EDGAR A. PEARLSTEIN, *University of Nebraska*.—The change in the heat of solution of sodium choride caused by x irradiation has been measured. The method consists of (1) preparing two identical samples, (2) irradiating one of them with 140-kv x rays and taking ultraviolet and visible spectra of it, (3) dissolving both in water in a differential calorimeter, and (4) measuring the temperature difference. The experiment has been carried out for a number of F-center densities between 2.4 and 6.4×10^{17} F centers/cm^3. In this range, a plot of stored energy vs F-center concentration is a straight line with slope of about 8.8 ev/F center. At 2.6×10^{17} centers/cm^3 the average stored energy per center is about 3.2 ev. Additional data will be presented.

* This research was supported in part by the U. S. Atomic Energy Commission.

D10. Transient Production of F Centers in Sodium Chloride Single Crystals. VINCENT R. HONNOLD AND JAMES P. NOLTA, *Hughes Aircraft Company*.—Transient production of F centers has been observed in sodium chloride using the pulsed, bare critical reactor facility (Godiva II) of the Los Alamos Scientific Laboratory. It has been possible to observe the generation and decay rates of the F centers produced by this high-flux (10^{16} fissions per pulse), short-duration (100 μsec wide at half-peak) pulse of gammas and neutrons because of the fast rise time ($\sim$20 μsec) of this pulse. The color center density generated in the crystal was observed by monitoring the change in optical transmission through the crystal using a cadmium sulfide photoresistor. The observed data, together with rate equations first proposed by Mador *et al.*[1] seems to support two possible models: either indirect production by a modified Varley mechanism[2] or indirect production from a positive and negative ion vacancy pair. Correlating data for this transient production of F centers in sodium chloride has been obtained using gammas produced by a 1-Mev electron beam generator. Here again the same rate equations yield satisfactory results.

[1] I. L. Mador, R. F. Wallis, M. C. Williams, and R. C. Herman, Phys. Rev. 96, 617 (1954).
[2] J. H. Crawford, Jr., and C. M. Nelson, Phys. Rev. Letters 5, 314 (1960).

D11. F Center Formation in LiH Crystals at Low Temperatures.* F. E. PRETZEL, G. V. GRITTON,† C. C. RUSHING,† R. J. FRIAUF,† W. B. LEWIS, AND P. WALDSTEIN, *Los Alamos Scientific Laboratory*.—Single crystals of lithium hydride have been prepared from the melt by a method previously described[1] utilizing combinations of the stable isotopes to examine the ESR and optical absorptions of color centers produced in irradiated samples. Papers in publication describe the characterization and identification of the F band at 2.4 ev. F-center production was examined in the 80°–250°K temperature range by means of x rays, pile neutrons, and tritium β particles from LiT included in several crystals. Results are comparable to those obtained with alkali halides if the low oscillator strength (0.2 maximum) of the F band is used. The most extensive study at higher radiation doses was carried out with samples cleaved from a single crystal containing 5.5 mole% LiT. Two mechanisms for F-center production (one irreversible) exist in these samples, which were examined concurrently by optical absorption, ESR, and flotation measurements.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† Guest scientist.
[1] F. E. Pretzel, Bull. Am. Phys. Soc. Ser. II, 2, 155 (1957).

D12. Magnetic and Color Centers in KCl. EDWARD SONDER, *Oak Ridge National Laboratory*.*—The temperature dependence of the magnetic susceptibility and the absorption spectra of additively colored specimens were measured before and after bleaching and annealing treatments. A 30% decrease in the area of the F band and a larger (33–50%) decrease in the density of magnetic centers were caused by bleaching in the F-band tail and annealing near 105°C. The fact that the change in magnetic centers exceeds that of the F band indicates not only that most aggregate centers are nonmagnetic but that a nonmagnetic center exists, which absorbs F light. The results are most easily accounted for by van Doorn and Haven's model of the M center.[1] According to it, the M center is simply a close pair of two F centers, which absorbs both in the M and F bands. Such a two-electron system would, due to pairing, not yield any spin paramagnetism yet would contribute to the F-band absorption.

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.
[1] C. Z. van Doorn and Y. Haven, Ned. Tijdschr. Natuurk. 26, 216 (1960).

D13. Stages in the Annealing of Radiation Induced Color Centers and Defects in Al_2O_3.* PAUL W. LEVY, *Brookhaven National Laboratory*.—Reactor irradiated Al_2O_3 contains absorption bands at 6.02, 5.35, and 4.85 ev. Their annealing characteristics may be determined by heating crystals for a fixed period, at a series of temperatures differing by a fixed increment, starting at the irradiation temperature and continuing until all color is removed, usually 700°–800°C. After each anneal optical absorption measurements are made at room temperature. Also, crystals are irradiated with gamma-ray doses sufficient to produce equilibrium coloring which shows that most of the color removed during each anneal is due to electronic process. In crystals irradiated at 65°C and heated for 40 min at each temperature, the defect annealing occurs in three principal stages. For the 6.02-ev band at 100° to 340°, 340° to 500°, and 500° to 730°C. The stages for the 5.35- and 4.85-ev bands are 100° to 370°, 370° to 490°, and 490° to 730°C. Crystals irradiated at 200°C show little annealing in the first two stages. Gamma-ray irradiation restores the 6.02 band in all three stages but diminishes the 5.35 and 4.85 band during only the second stage. In addition to the principal stages, there is evidence of "fine structure" in the annealing.

* Research performed under the auspices of the U. S. Atomic Energy Commission.

D14. Ultraviolet Absorption Bands of KI Dissolved in KCl.* HERBERT MAHR, *Cornell University* (introduced by P. L. Hartman).—Absorption bands due to small admixtures of KI in KCl were observed in single crystals. At room temperature only one absorption band due to KI is detectable. Position and half-width of this band are 6.6 and 0.3 ev, respectively. The height of the absorption maximum is proportional to the KI concentration in the melt, ranging from 10^{-3} to 5×10^{-3} mole fraction KI. At liquid-nitrogen temperature a second band appears right at the edge of the fundamental absorption of KCl. The results will be discussed and compared with measurements of pure KI. The oscillator strengths of the bands were determined by use of Smakula's formula.

* Work supported by the Office of Naval Research and the Advanced Research Projects Agency.

MONDAY AFTERNOON AT 1:30

Criscuolo Hall

(B. LAX presiding)

Cyclotron and Magneto-Plasma Resonance

Invited Papers

DA1. Optical Maser Oscillations in a Gaseous Discharge. A. JAVAN, *Bell Telephone Laboratories, Inc.* (30 min.)

DA2. Electron Hole Plasmas in Semiconductors—Self-Pinching and Oscillations. MAURICE GLICKSMAN, *RCA Laboratories.* (30 min.)

Contributed Papers

DA3. Quantum Effects in Cyclotron Resonance of Holes in Germanium. J. C. HENSEL, *Bell Telephone Laboratories, Inc.*—New cyclotron resonance lines have been observed in germanium using a millimeter-wave Zeeman spectrometer. These lines are believed to arise from the quantum effects originating from the degeneracy of the valence band edge as first predicted by Luttinger and Kohn.[1] Measurements were made at 56 kMc/sec and temperatures near 1.3°K. Carriers of both signs were introduced into the sample by white light. Line broadening and other microwave heating effects were avoided by operating the spectrometer at ultra-low power levels ($<10^{-7}$ w). Under these conditions the electron resonances have $\omega\tau\sim350$. The samples were high purity p-type Ge slices oriented so the magnetic field could be rotated in the (110) plane. Up to 18 new lines have been observed for a given orientation of the crystal. In addition to the resonances near the heavy hole reported by Fletcher *et al.*,[2] considerable structure has been uncovered near the light-hole and in the intermediate mass regions. The anisotropy of some of the lines has been determined.

[1] J. M. Luttinger and W. Kohn, Phys. Rev. 97, 869 (1955); J. M. Luttinger, *ibid.* 102, 1030 (1956).
[2] R. C. Fletcher, W. A. Yager, and F. R. Merritt, Phys. Rev. 100, 747 (1955).

DA4. Observation of Quantum Effects in Germanium and Silicon at Millimeter Wavelengths. J. J. STICKLER, C. RAUCH, H. J. ZEIGER, AND G. S. HELLER, *Lincoln Laboratory,** *M.I.T.*—Quantum effects have been observed in p-type germanium and silicon at 4 and 2 mm using cavity spectrometers with light modulation. The observations were made at 1.2°K and above as a function of crystal orientation. Measurements on germanium at 2 mm and 1.2°K were in essential agreement with the 1.25-cm wavelength data of Fletcher, Yager, and Merritt.[1] Additional lines not reported by Fletcher were observed in the vicinity of the classical heavy hole in the [100] direction and in the vicinity of the classical light hole in all directions. In the 2-mm data the classical heavy and light hole resonances occurred only above 4.3°K. For the case of silicon, observations were made at 2 mm and from 1.2° to 4.3°K. Experimental data along with preliminary analysis of the results using Luttinger's theory[2] will be presented.

* Operated with support from the U. S. Army, Navy, and Air Force.
[1] R. C. Fletcher, W. A. Yager, and F. R. Merritt, Phys. Rev. 100, 747 (1955).
[2] J. M. Luttinger, Phys. Rev. 102, 1030 (1956).

DA5. Landau-Level Investigation in PbS, PbSe, and PbTe.* P. J. STILES, E. BURSTEIN, AND D. N. LANGENBERG, *University of Pennsylvania.*—The low-temperature electron and hole mobilities in the PbS group of compounds are high, even at relatively high carrier densities. In addition, there is no appreciable freeze-out of carriers at liquid-helium temperatures. Both of these properties are due in part to the relatively high dielectric constants. These properties lend themselves to studies of such phenomena as Azbel-Kaner type cyclotron resonance, ordinary cyclotron resonance, and de Haas-van Alphen type oscillations. PbTe and PbSe, which resemble bismuth in effective masses and relaxation times, appear best to satisfy the requirements for Azbel-Kaner type experiments at millimeter wavelengths for carrier concentrations of the order of 10^{18}/cm^3. It should also be possible to observe ordinary cyclotron resonance in these materials at these wavelengths by using thin sections. All these compounds should exhibit de Haas-van Alphen and related effects since they readily satisfy the condition that $\epsilon_F \gg k(T+T_b)$, where kT_b is the broadening of the Landau levels. Preliminary attempts to observe the Azbel-Kaner resonance in PbTe have not yet been successful. However, well defined de Haas-van Alphen oscillations in the magnetic susceptibility, have been observed in PbTe.

* Research supported in part by the U. S. Atomic Energy Commission.

DA6. Transport Studies in Germanium by Cyclotron Resonance Techniques. R. E. MICHEL AND B. ROSENBLUM, *RCA Laboratories, Princeton.*—The width of a cyclotron resonance line is a direct measure of the current relaxation time and the integrated intensity of the line (with respect to magnetic field) is proportional to the carrier concentration. Measurements of the electron cyclotron resonance linewidth in highly purified germanium as a function of temperature in the range 2°–20°K shows a region (2°–10°K) where phonon scattering is dominant and a region where ionized impurity scattering is important because of the thermally excited carriers. In the phonon dominant region the relaxation time can be fitted to a $T^{-\frac{3}{2}}$ law plus a temperature-independent correction for neutral impurity scattering. The ionized impurity scattering for about 7×10^{13} impurities at 14°K was in rough agreement with the Brooks-Herring formula. The number of ionized carriers was determined by the plasma shift of the cyclotron resonance line. The lifetime of optically excited electrons and holes was determined to be proportional to $T^{-\frac{3}{2}}$ in an n-type sample ($N_D\approx10^{14}$/cc) and independent of temperature in a highly purified sample. In observing the cyclotron resonance with microwave powers in the microwatt region, the carriers are heated above the lattice temperature. The mobility of such hot electrons has been studied and is proportional to (incident power)$^{-\frac{1}{2}}$ as is expected for spontaneous phonon emission.

DA7. Multicomponent Magnetoplasma Resonances in Germanium. B. ROSENBLUM AND R. E. MICHEL, *RCA Laboratories, Princeton.*—Magnetoplasma resonances of the multicomponent plasma consisting of the light and heavy holes in germanium have been observed at 24 kMc. The carrier con-

centration and therefore the plasma frequency was controlled by varying the temperature of a small ellipsoid of p germanium in the 10°–15°K region. The preliminary experiments appear to be in qualitative agreement with solutions of the coupled oscillator equations written by Kittel. In solving these equations we assumed that the holes were two coupled systems with isotropic masses. Electron magnetoplasma resonance in germanium was also observed as a function of the orientation of the magnetic field in the crystal. The line, although broad, appeared to be single. The anisotropy was less than ten per cent when the plasma frequency was two or three times the cyclotron frequency. A careful check of the carrier concentration and the sample shape dependance of the plasma frequency can confirm the expected redundancy of any Lorentz or cavity contribution to the local field acting on the carrier. Present results are interpretable without such corrections. Light modulation is not used in the present experiments; the line shapes are therefore simple Lorentzian in contrast to those previously observed.

DA8. Magnetoplasma Reflection in InAs and GaAs.* PAUL D. MAKER, JOHN BAKER, AND DAVID F. EDWARDS,† *The University of Michigan.*—Magnetoplasma reflection measurements have been made on n-type samples of InAs and GaAs. On using plane polarized radiation ($E \perp H$) the single zero-field plasma reflection minimum splits into two minima under applied magnetic fields with separation equal to the cyclotron frequency. The electron effective mass has been estimated from this splitting. Typical values for InAs are $m^*/m = 0.051$ for an electron concentration of 1.8×10^{18} cm^{-3}. Small inhomogenities in carrier concentration can broaden these lines and in some cases completely eliminate one of the reflection minima. Plasma reflection measurements have been used to examine inhomogenities in samples, and concentration differences as small as 1.0% have been measured. Data will be presented for the variation of effective mass with carrier concentration.

* Work was conducted by Project MICHIGAN under a Department of the Army contract administered by the U. S. Army Signal Corps.
† Present address: Lincoln Laboratory, M.I.T.

DA9. Microwave Stimulated Resistance Oscillations in Germanium at 4°K. H. KROEMER, *Varian Associates.*—The electrical resistance of several germanium crystals at 4°K was found to oscillate strongly if the crystals were subjected to a microwave field, in addition to being illuminated. The oscillations consist of regularly spaced short pulses (about 3 μsec long) rather than being sinusoidal. The oscillations set in abruptly at a certain microwave power level. They disappear again at higher powers, before ionization breakdown occurs. The pulse repetition frequency is proportional to the illumination level, typical frequencies being in the kilocycle range. The effect was found in both n- and p-type germanium, and for several crystal orientations. It is believed to be due to a change in carrier mobility through microwave heating which in turn produces a change in the microwave coupling. In this way a thermal runaway occurs, leading to relaxation oscillations.

DA10. Charging Surface Activity in the Oscillistor. K. T. ROGERS, *Varian Associates.*—In their studies of the "oscillistor,"[1] Larrabee and Steele[2] find that to obtain oscillations it is necessary that both parallel and transverse magnetic field components be present. (Compare with the work of Cardona and Ruppel.[3]) The transverse field points to importance of pair accumulation at a "Hall surface." There should also be some "charging" at the surfaces to which carriers tend in drifting *parallel* to the magnetic field, and we consider the effects at these "charging surfaces" as well as those at the Hall surface. We find that modifying the "charging" by applying high polarizing electric fields alters oscillistor periods. We find symmetries under reversal of magnetic field and/or angle of field that can be explained only if behavior at both sets of surfaces is considered. Thus we feel that behavior at both sets of surfaces is important to the mechanism and we present the evidence from these experiments.

[1] Current oscillations in an elongated semiconductor specimen placed in a magnetic field with both electrons and holes contributing to the conduction.
[2] R. D. Larrabee and M. C. Steele, J. Appl. Phys. 31, 1519 (1960).
[3] M. Cardona and W. Ruppel, J. Appl. Phys. 31, 1826 (1960).

DA11. Oscillations in Semiconductor Plasmas. MAURICE GLICKSMAN, *RCA Laboratories.*—Oscillations have been observed[1,2] in semiconductors containing electron-hole plasmas, situated in a magnetic field parallel to the current flow. It is suggested that these oscillations are part of a class of diffusion instabilities found in gaseous plasmas.[3] A theory applicable to the electron-hole plasma in semiconductors has been derived, and compared with the experiments in germanium[1] and indium antimonide.[2] Calculated values for the threshold longitudinal magnetic fields and the lowest oscillation frequencies are in fair agreement with the observations.

[1] R. D. Larrabee and M. C. Steele, J. Appl. Phys. 31, 1519 (1960).
[2] M. Glicksman and R. A. Powlus, Phys. Rev. (to be published).
[3] B. B. Kadomtsev and A. V. Nedospasov, J. Nuclear Energy, Part C: Plasma Phys. 1, 230 (1960).

MONDAY AFTERNOON AT 2:00

Ballroom, Herrman Hall

(G. BIRNBAUM presiding)

Electron Spin, Resonance I

E1. Paramagnetic Resonance of Cu^{3+} in Al_2O_3. S. GESCHWIND AND J. P. REMEIKA, *Bell Telephone Laboratories.*—The paramagnetic resonance of Cu^{3+} (configuration $3d^8$ which is isoelectronic with Ni^{2+}) has been observed for the first time. The Cu^{3+} entered substitutionally for the Al in the Al_2O_3 lattice. An axial spectrum with $S=1$ is observed with a hfs pattern of four lines for each of the two fine structure components corresponding to the Cu nuclear spin of $I=\frac{3}{2}$. While the hfs components of the Cu^{63} could not be resolved from those of the Cu^{65}, a broadening of the outer hyperfine components is observed in good agreement with the known Cu nuclear magnetic moment ratios. The results at low temperature are fitted at 24 kMc with the following parameters: $D = -0.18838 \pm 4$ cm^{-1}, $g_{\parallel} = 2.0784 \pm 5$, $g_{\perp} = 2.0772 \pm 5$, $A(Cu^{63}) = -64.6 \pm 0.6 \times 10^{-4}$ cm^{-1}, $B(Cu^{63}) = -60.2 \pm 0.6 \times 10^{-4}$ cm^{-1}. The sign of D was found by observing the relative intensity of the fine structure components at low temperature. The sign of A was found from the second-order shifts in the hfs intervals. These results for Cu^{3+} are compared with those for Ni^{3+} in the same lattice in terms of the excited states of these ions.

E2. Electron-Nuclear Interactions of Cu^{2+} in Sapphire. J. EISINGER, W. E. BLUMBERG, AND S. GESCHWIND, *Bell Telephone Laboratories, Inc.*—The Cu^{2+} ion in sapphire whose microwave spectrum is discussed in the preceding abstract was studied in considerable detail by use of the electron nuclear resonance (ENDOR) technique. All transitions of the type $\Delta M_S=0$, $\Delta m_I=\pm 1$ for the levels $M_S=\pm\frac{1}{2}$ were observed for Cu^{63} and Cu^{65} with linewidths of about 50 kc with $H_0=6300$ oe parallel to the c axis and $T=1.3°K$. The observed ENDOR spectrum could be fitted satisfactorily only by postulating an effective field at the nucleus equal to $(1+\delta)H_0$, where $\delta=0.0135\pm0.0022$. δ reflects the field-dependent term which arises in second order from the $\mathbf{I}\cdot\mathbf{L}$ and $\mathbf{H}\cdot\mathbf{L}$ interactions. Positive δ's of this order of magnitude are to be expected for all transition metals. The interaction constants with their probable errors are $A_{63}=-192.982\pm0.007$ Mc/sec, $A_{65}=-206.715\pm0.008$ Mc/sec, $B_{63}=-179.6\pm1.2$ Mc/sec, $B_{65}=-192.4\pm1.3$ Mc/sec, $e^2qQ_{63}=-0.058\pm0.004$ Mc/sec, where A and B refer to the parallel and perpendicular hyperfine interactions, respectively. From the above the hyperfine anomaly $\Delta=(A_{63}/A_{65})\times(g_{65}/g_{63})-1=(0.015\pm0.005)\%$. Since Δ for an $s_{\frac{1}{2}}$ electron is $(0.015\pm0.002)\%$ for Cu one can conclude that $s_{\frac{1}{2}}$ electrons polarized by s-d interactions are largely responsible for the observed $A(<0)$.

E3. Spin Resonance of Gamma-Ray Irradiated α-Al_2O_3.* O. R. GILLIAM AND C. G. YOUNG, *University of Connecticut*, AND P. W. LEVY, *Brookhaven National Laboratory*.—A paramagnetic resonance absorption has been observed at 9.2 kMc in Co^{60} gamma-ray irradiated single crystals of Linde α-Al_2O_3. This resonance line is about 40 gauss wide at inflection points with $g\approx2.01$. There is some evidence of a slight shift of g with orientation, but the presence of strong impurity resonances has prevented accurate measurements to date. The growth of this line saturates with less than 5×10^6r at about 10^{18} spins. Most samples were irradiated at 77°K rather than 300°K because of the enhancement in signal. The intensity of the absorption in samples irradiated at 77°K drops about a half after one hour at 200°K. The resonance remains for at least six months at room temperature. Growth saturation, stability and annealing behavior correlate with the behavior of γ-induced optical absorption bands. The resonance is detectabie with 5×10^3r. Irradiation up to 10^7r causes no increase in intensity over a 5×10^4-r dose.

* Supported by U. S. Atomic Energy Commission.

E4. Spin Resonances in Reactor-Irradiated α-Al_2O_3.* C. G. YOUNG AND O. R. GILLIAM, *University of Connecticut*, AND P. W. LEVY, *Brookhaven National Laboratory*.—Single crystals of α-Al_2O_3 (Linde) irradiated several hours at 100°C in the BNL reactor show an ESR line with $g\approx2.01$. The linewidth is 26 gauss at 77°K and at 9.2 kMc. This absorption is intense after one week of irradiation; such a dosage also causes 12 or more weaker lines with trigonal symmetry centered about the main line with maximum splitting of about 1600 gauss. All lines anneal out at 500°C. If, subsequent to reactor irradiation, the sample receives 10^4-r Co^{60} gamma-ray irradiation at 77°K, a strong 3-line spectrum is obtained characterized by: no variation about c axis, zero line separation and crossover for 55° orientation, intensity ratio approximately 3:4:3 at 90°, high field line slightly more intense of outermost lines of 0°, $g_\perp>g_\parallel>g$ electron, and widths of 22 gauss. This fine structure corresponds to a center with spin $S=\frac{3}{2}$, more than half-filled shell, and $D=+1.0\pm0.1$ kMc. No growth saturation or bleaching by room light were observed; however, this 3-line spectrum disappears with a 1-hr anneal at 200°K.

* Supported by U. S. Atomic Energy Commission.

E5. Paramagnetic Resonance of Trivalent Fe^{57} in Zinc Oxide. W. M. WALSH, JR., *Bell Telephone Laboratories, Inc.*—Single crystals of ZnO grown from flux by R. C. Linares, Jr. have been examined at 11 kMc. Excessive microwave loss has been considerably reduced by lithium doping.[1] The spectra of $Fe^{3+}(^6S)$ in two sites equivalent save for a 60° relative azimuthal rotation (presumably the two tetrahedral metal ion sites) have been observed in several samples. These spectra may be described by the axially symmetric spin-Hamiltonian appropriate to $S=\frac{5}{2}$ with the following parameters: $g=2.0060$, $D=-0.0594$ cm^{-1}, $a-F=0.00356$ cm^{-1}. Numerical diagonalization of the secular determinant will permit separate evaluation of the cubic and axial fourth-order coefficients, a and F. Comparison will be made with parameters found for tetrahedrally coordinated Fe^{3+} in $YGaG^2$. The hyperfine structure due to Fe^{57} has also been clearly resolved in a sample doped by diffusion from enriched Fe_2O_3. The coupling constant, $|A|=0.00090$ cm^{-1}, found in ZnO is reduced by 20% with respect to the value found in MgO[2]. This effect is three times larger than that found for isoelectronic Mn^{55} in the same host crystals.

[1] A. R. Hutson, Phys. Rev. Letters **4**, 505 (1960).

E6. Hyperfine Structure of Fe^{57} in MgO. E. S. ROSENVASSER, *Columbia University*, AND G. FEHER,* *University of California*.—The hyperfine structure of Fe^{57} in single crystals of MgO containing Fe^{3+} as an impurity was resolved completely[1] at 1.3°K and ~9000 Mc. The paramagnetic resonance spectrum showed two satellites, one on either side of the main $(\frac{1}{2}\leftrightarrow\frac{1}{2})$ transition, with integrated intensities corresponding to the natural abundance of Fe^{57}. The total separation of the satellite lines was found to be 10.8 ± 0.2 ϕ corresponding to an internal field at the Fe^{3+} nucleus of 2.2×10^5 ϕ. This value is, within a few percent, the same as for the isoelectronic Mn^{++} impurity in MgO. The origin of this hyperfine field has been shown by several authors to be due to the polarization of the core s electrons by the $3d$ electrons.[2]

* Work performed while at the Bell Telephone Laboratories, Murray Hill, New Jersey.

[1] The hf interaction had been partially resolved at higher temperatures by J. E. Wertz (private communication).

[2] J. H. Wood and G. W. Pratt, Jr., Phys. Rev. **107**, 995 (1957); V. Heine, *ibid.* **107**, 1002 (1957); A. J. Freeman and R. E. Watson, *ibid.* **120**, 1125, 1134 (1960); D. A. Goodings and V. Heine, Phys. Rev. Letters **5**, 370 (1960).

E7. Paramagnetic Resonance of ZnTe:Mn.† G. H. AZARBAYEJANI, C. KIKUCHI, AND D. MASON, *University of Michigan*.—Spin resonance measurements of ZnTe containing about 0.01% Mn^{++} have been carried out to augment the information on Mn^{++} ions in the cubic $A_{II}B_{VI}$ compounds, ZnS and CdTe, reported earlier.[1,2] The g value at 77°K is about 2.005. The cubic field parameter $3a$ is about 0.00348 cm^{-1} at 4.2°K. This is to be compared with 0.00233 cm^{-1} and 0.0084 cm^{-1} for ZnS and CdTe, respectively. Measurements indicate that the hfs coupling constant A is temperature dependent, having the values 62.2, 61.0, and 60.5 gauss at 300°, 77°, and 4.2°K, respectively. This temperature dependence is in contrast to that of CdTe, for which preliminary measurements give 60.6, 61.7, and 61.6 gauss at 300°, 77°, and 4.2°K, respectively.

† Supported in part by the Air Force Office of Scientific Research.

[1] L. M. Matarrese and C. Kikuchi, Phys. Rev. **100**, 1232 (1955).

[2] J. Lambe and C. Kikuchi, Phys. Rev. **119**, 1256 (1960).

E8. Paramagnetic Resonance of Cr^{3+} in GASH.* G. MAKHOV AND O. RISGIN, *Institute of Science and Technology, The University of Michigan* (introduced by D. F. Edwards).—X-band paramagnetic resonance of Cr^{+++} in GASH (guanadine aluminum sulfate hexahydrate) has been observed at three temperatures, 300°, 77° and 4.2°K. The observed spectra can

be accounted for by a simple axial field model with the axial field component D increasing with decreasing temperature. At 4.2°K superhyperfine structure was observed in the $\frac{1}{2} \rightarrow -\frac{1}{2}$ transition, and was ascribed to contact interaction between the nuclear magnetic moments of protons in the waters coordinated to the Cr^{3+} and the Cr^{3+} electronic moment. No effect of ferroelectric domains was observed. The crystal lends itself well to stimulated emission and to ENDOR experiments.

* This work was conducted by Project MICHIGAN under a Department of the Army contract administered by the U. S. Army Signal Corps.

E9. Electron Nuclear Double Resonance Effects in GASH.* O. RISGIN AND G. MAKHOV, *The University of Michigan* (introduced by D. F. Edwards).—Electron nuclear interaction existing in GASH assumes two forms. First, the usual decrease has been observed of the EPR absorption signal with application of NMR power at frequencies of Al_{27}, proton, etc., resonance. Secondly, with GASH operated as maser, there exists an interaction between the maser output and applied rf power of the order of megacycles. This interaction manifests itself as converter action; i.e., several orders of sidebands appear about the center frequency. An interpretation of the above phenomenon is based on experimental evidence that the EPR line of GASH is inhomogeneously broadened to a substantial degree. The application of nuclear frequency rf power induces hyperfine transitions, and connects the normally isolated spin packets existing within the linewidth. In the case of the maser oscillator this results in the appearance of secondary oscillators which may be regarded as sidebands. Oscillation occurs at the center of the gain envelope; hence, sidebands are symmetric. Conversely, an external signal can be positioned anywhere within the envelope; hence, a single sideband may be obtained.

* Work was conducted by Project MICHIGAN under a Department of the Army contract administered by the U. S. Army Signal Corps.

E10. Electron Spin Resonance in Irradiated KH_2PO_4 and KD_2PO_4.† F. JEFFERS, *New Mexico A. & M.*, AND P. E. WIGEN AND J. A. COWEN,* *Lockheed Research Laboratories.*—Electron spin resonance has been observed in electron irradiated KH_2PO_4 and KD_2PO_4 in the ferroelectric state. The spectra in the deuterated crystal consists of two essentially isotropic lines split by 50 gauss with an average $g=2.02$. We attribute this splitting to an isotropic hyperfine interaction with the phosphorous nucleus. The spectra in the normal crystal consists of eight anisotropic lines which can be associated in four pairs, each pair showing a 50 gauss splitting. For rotation about the ferroelectric axis the lines show fourfold symmetry and an average $g=2.03$. We attribute the anisotropic splitting to a hyperfine interaction with protons which is not resolved in the deuterated crystal due to the smaller moment of the deuteron. The data does not fit a simple analysis involving as interaction with a single proton but rather appears to be due to an $I=\frac{3}{2}$ hyperfine term.

† This work supported by the National Science Foundation at Michigan State University where one of the authors (F.J.) was an NSF undergraduate research fellow.

* On leave from Michigan State University.

E11. Infrared Pumped Paramagnetic Excited State in Phosphorus-Doped Silicon.* A. HONIG, *Syracuse University.*—For a particular crystal of silicon containing $\sim 10^{16}$ phosphorus impurities/cm³, an excited state has been appreciably populated by photoionizing the neutral phosphorus impurities, and electron spin resonance in the excited state has been observed. The lifetime of an electron in the excited state exceeds several hours at liquid helium temperatures, but the state can be rapidly emptied by infrared radiation of wavelength greater than $\sim 30\,\mu$. This radiation has insufficient energy to photoionize phosphorus impurities from their ground state, but has sufficient energy to depopulate the excited state. The electron spin resonance associated with this excited state is a single line at $g \cong 1.998$, and the spin-lattice relaxation time is only slightly shorter than the relatively long times[1] associated with the 2 hyperfine lines of the ground-state spin resonance. Identification of this excited state as part of the fivefold nearly degenerate $1S$ state in the Kohn-Luttinger theory[2] of impurity states in silicon is suggested by the experiments. Other conceivable identifications will be discussed, as well as possible explanations of why most silicon samples do not exhibit this photoinduced resonance.

* Supported in part by the Air Force Office of Scientific Research.

[1] A. Honig and E. Stupp, Phys. Rev. 117, 69 (1960).

[2] W. Kohn and J. M. Luttinger, Phys. Rev. 98, 915 (1955).

E12. Spin Resonance of Acceptor Impurities in Silicon. G. W. LUDWIG AND H. H. WOODBURY, *General Electric Research Laboratory.*—Spin resonance of column III acceptor elements in silicon crystals subjected to uniaxial stress has been reported recently by Feher *et al.*[1] We have carried experiments on these acceptors (B, Ga, Al, and In) to considerably higher stresses ($\sim 10^4$ kg/cm²), and have investigated the temperature range 1.3 to 10°K. The width of the single line detected at low stresses passes through a minimum at intermediate stresses. Structure, apparently due to hyperfine interaction, has been resolved at larger stresses in some cases. The spin-lattice relaxation time increases by as much as a factor of 10^5 with increasing stress. Resonance due to the deep-level acceptor zinc has also been observed.

[1] G. Feher, J. C. Hensel, and E. A. Gere, Phys. Rev. Letters 5, 309 (1960).

E13. Impurity Studies in Compound Semiconductors by Electron Spin Resonance. H. H. WOODBURY AND G. W. LUDWIG, *General Electric Research Laboratory.*—Electron spin resonance techniques have been extremely useful for obtaining information about dilute impurity systems. However, relatively little work has been reported on single crystals of the II–VI and III–V type semiconductors. These systems are of interest in crystal field studies in that they present sites of four-fold (tetrahedral) symmetry. Table I presents recent results obtained by us on such semiconductors at a temperature of 10°K. For V and Co in CdS the hyperfine interaction A is given parallel and perpendicular to the c axis. A, a, and D are in units of 10^{-4} cm^{-1}. These results, others on Co^{++} recently obtained by us,[1] and those of other investigators will be presented and discussed.

TABLE I.

Crystal	Impurity	S	g	A	
GaP	Mn		2.002	55	
GaP	Fe^{3+}	5/2	2.025		$a=+390$
ZnSe	Mn^{++}	5/2	2.0051	61.7	
ZnTe	V		1.917	57.8	
ZnTe	Mn^{++}	5/2	2.0128	−56.2	$a=+30$
CdTe	Mn^{++}	5/2	2.0069	57.3	
CdS	V^{2+}	1	1.933	63(∥) 66(⊥)	$D=1130$
CdS	Co^{++}	3/2	2.269	4.6(∥) <12 (⊥)	$D>2.10^4$

[1] F. S. Ham, G. W. Ludwig, G. D. Watkins, and H. H. Woodbury, Phys. Rev. Letters 5, 468 (1960).

MONDAY AFTERNOON AT 2:00

Copper Cup Room, Herrmann Hall

(U. FANO presiding)

Theory

EA1. Dielectric Constant with Local Field Effects Included. NATHAN WISER, *University of Chicago* (introduced by M. H. Cohen).—The expression for the longitudinal dielectric constant of a many-electron system in a periodic potential given by Cohen and Ehrenreich[1] has been generalized by the inclusion of local field effects, paying careful attention to the relationship between microscopic and macroscopic quantities. The result has the following form for long wavelengths and low frequencies: $\epsilon=\epsilon_c-4\pi Ne^2/m_a\omega^2$. The second term is the usual acceleration term, N and m_a being an appropriate carrier density and an appropriate average effective mass, respectively. This term does not contain a local field correction. The first term, ϵ_c, is the analog of the ordinary atomic polarization and does contain a local field correction which has been calculated explicitly for the weak and tight binding limits. Evaluation of ϵ_c for more realistic models of crystals will be discussed.

[1] H. Ehrenreich and M. H. Cohen, Phys. Rev. 115, 786 (1959).

EA2. Effect of Quasiparticle Lifetime on Superconducting Transition Temperature. H. SUHL, *University of California, La Jolla.*—At a temperature T above the superconducting transition temperature T_s, the amplitude of a Cooper pair state (if it existed), would oscillate with a frequency ω given by $V\int d\epsilon[\tanh\frac{1}{2}\epsilon/kT]/(2\epsilon+\omega)=1$, where V is the strength of the interaction, ϵ is the quasi-particle energy measured relative to the Fermi energy, and the integration extends over that vicinity of the Fermi surface in which V is attractive. This equation has no roots for $T>T_s$. At $T=T_s$, the root is zero. For $T<T_s$ there are two roots $\omega=\pm i\gamma(T)$ where γ is real, and steadily increases with diminishing T.[1] Thus the Fermi state is unstable. When ϵ is complex, i.e., for a finite quasiparticle lifetime $1/\Gamma$, there are still no roots for $T>T_s$, and for $T<T_s$ we have $\omega=\pm i\gamma+i\Gamma$. Collapse of the Fermi state is therefore deferred until $T<T_s'$ where T_s' is given by $\gamma(T_s')=\Gamma$. In the range $T_s'<T<T_s$, Cooper pairs exist, but have a limited lifetime $(2\Gamma-\gamma)^{-1}$. The particular case of phonon scattering will be discussed.

[1] Helpful discussions of this equation with L. R. Walker of Bell Telephone Laboratories are acknowledged.

EA3. Anharmonic Contribution to the Energy of a Dilute Electron Gas Interpolation for the Correlation Energy. W. J. CARR, JR., *Westinghouse Research Laboratories*, R. A. COLDWELL-HORSFALL, *University of Maryland*, AND A. E. FEIN, *Westinghouse Research Laboratories.*—The first anharmonic contribution to the ground state energy of a bcc lattice of electrons, oscillating in a uniform background positive charge, has been calculated. The result is $-0.73\ r_s^{-2}$ ry, with r_s the radius, in Bohr units, of the sphere equivalent in volume to that occupied per electron. Combining this term with previous results gives for the ground state energy of a dilute electron gas the expression

$$E=E_{\text{exp}}-1.792r_s^{-1}+2.65r_s^{-\frac{1}{2}}-0.73r_s^{-2}+0(r_s^{-\frac{1}{2}}),$$

where E_{exp} comes from the overlapping of electronic wave functions and falls off exponentially with $r_s^{\frac{1}{2}}$; while the r_s^{-1} and $r_s^{-\frac{1}{2}}$ terms are, respectively, the Coulomb energy of a bcc lattice and the zero point energy of the electrons. The "correlation" energy corresponding to the above expression as well as the kinetic and potential parts, has been plotted and an interpolation has been made between the low-density curve and the high-density expression of Gell-Mann and Brueckner. The magnitude of the correlation energy so obtained for the intermediate region $2<r_s<6$ is approximately 15 to 30% smaller than previous estimates. The interpolated curves give strong evidence that the next term in the above low-density expansion for E is approximately $-0.8\ r_s^{-\frac{1}{2}}$. On the assumption that the high-density expression is rapidly converging near $r_s=1$, it also is predicted that the r_s term in the high-density expansion will be approximately $-0.02\ r_s$.

EA4. Anharmonic Contributions to Specific Heat.* JOSEPH M. KELLER AND DUANE C. WALLACE,† *Iowa State University.*—Appreciably above the Debye temperature, the lattice specific heat (at constant volume) of a solid due to a harmonic lattice potential is independent of temperature. Including anharmonic parts of the lattice potential makes a contribution to specific heat nearly linear in temperature. Terms in the potential cubic and quartic in lattice displacements contribute, respectively, positively and negatively to specific heat, and the net sign is not clear. Calculations on crystals with a single atom per unit cell, neglecting dependence of phonon frequency on polarization and on direction of propagation, show that the net effect is one of specific heat decreasing as temperature increases. The calculations are based on central Lennard-Jones forces in bcc and fcc crystals. Nearest and next-nearest neighbor forces are considered, and phonon dispersion is included approximately.

* This work was performed in the Ames Laboratory of the U. S. Atomic Energy Commission.
† Present address: Sandia Corporation.

EA5. Anharmonic Corrections to Vibrational Thermodynamic Properties of Solids. I. The High Temperature Limit. R. A. COLDWELL-HORSFALL, *University of Maryland*, AND P. A. FLINN AND A. A. MARADUDIN, *Westinghouse Research Laboratories.*—Cubic and quartic anharmonic corrections to the Helmholtz free energy of a crystal have been derived as functions of temperature for a general force constant model of the crystal. The resulting expressions are evaluated in the high temperature limit for the case of a fcc lattice with nearest-neighbor central force interactions between atoms. These results are then applied to the calculation of the high-temperature anharmonic corrections to the specific heat at constant volume and to the thermal expansion.

EA6. Lattice Anharmonicity and Optical Absorption in Polar Crystals. II. Classical Treatment in the Linear Approximation. A. A. MARADUDIN, *Westinghouse Research Laboratories*, AND R. F. WALLIS, *U. S. Naval Research Laboratory.*—An expression for the elements of the dielectric susceptibility tensor for an ionic crystal has been derived in a manner analogous to that employed by Kubo[1] in his treatment of magnetic susceptibility. In the high-temperature (classical) limit, this expression reduces to the Laplace transform of the autocorrelation function of the single normal coordinate which interacts directly with the external radiation field. We have applied this formalism to the calculation of the high-temperature linear optical absorption coefficient of an anharmonic ionic crystal for which we have retained only cubic anharmonic terms in the lattice Hamiltonian. We have solved directly for the Laplace transform of the autocorrelation function to lowest order in the anharmonic coupling constant by solving the

equations of motion for the normal coordinates after they have been linearized. The linear absorption coefficient obtained from the susceptibility tensor is of Lorentzian form with a frequency-dependent damping constant which varies linearly with temperature. The absorption coefficient for a diatomic linear chain with nearest-neighbor interactions has been evaluated.

[1] R. Kubo, J. Phys. Soc. Japan 12, 570 (1957).

EA7. Lattice Anharmonicity and Optical Absorption in Polar Crystals. III. Quantum Theory. R. F. WALLIS, *U. S. Naval Research Laboratory*, AND A. A. MARADUDIN, *Westinghouse Research Laboratories.*—A quantum mechanical theory has been developed for the optical absorption associated with the lattice vibration of an ionic crystal. Cubic anharmonic terms in the potential energy are included. A generalized Weisskopf-Wigner time-dependent perturbation method has been employed to solve the quantum mechanical equations of motion in the limit of long times. The present treatment retains certain intermediate states which are omitted in a related treatment of Born and Huang. Qualitative information concerning the frequency dependence of the optical absorption is obtained by applying the general results to a simplified model of an ionic crystal. The temperature dependence of the absorption is investigated in the high-temperature limit.

EA8. Statistical Mechanics of Defect Containing Solids. A. R. ALLNATT AND M. H. COHEN, *University of Chicago.*—The analogies between properties of point defects in a solid and interacting solute particles in a solution are well known. However, the implications of the existence of such analogies in guiding a rigorous formulation of the statistical mechanics of defect solids has been little investigated apart from an early paper by Mayer.[1] A formalism for the statistical mechanics of point defects is being developed in which defect properties are separated in a manner analogous to the solute in the McMillan–Mayer theory of solutions. In this formalism the description of properties in terms of complexes such as vacancy pairs or higher aggregates must be reformulated in terms of the study of the distribution functions of various orders of the defects. The latter can be developed using the diagram techniques of imperfect gas and solution theory, using lattice summations in place of integrations over space; and the defect contributions to the equilibrium thermodynamic properties can also be studied. Effects of Coulomb interactions on defect concentrations in ionic crystals will be discussed.

[1] J. E. Mayer, *Phase Transformations in Solids*, edited by Smoluchowski, Mayer, and Weyl (John Wiley & Sons, Inc., New York, 1951), p. 38.

EA9. Quantum Statistical Solutions for a Driven, Damped Harmonic Oscillator. G. J. LASHER, *I.B.M., Yorktown.*—The equation of motion of the von Neumann density operator of a single harmonic oscillator in contact with a heat bath is found under the usual assumptions of time-dependent perturbation theory. This may be termed a special case of the Bloch-Wangsness equation,[1] but has been discussed by other authors[2] with different terminology. From this equation the equation of motion of the Wigner phase space density function[3] is derived. This is a partial differential equation in time and phase space; it has a general solution in terms of an infinite series of products of harmonic oscillator functions of position and momentum with relaxation times which are integer multiples of the classical relaxation time. Simple closed-form solutions are obtained for a time-varying driving force and a time-varying temperature of the heat bath.[4]

[1] R. K. Wangsness and F. Bloch, Phys. Rev. 89, 128 (1953); F. Bloch, *ibid.* 105, 1206 (1957); U. Fano, Revs. Modern Phys. 29, 74 (1957).
[2] M. Toda, J. Phys. Soc. Japan 13, 1266 (1958).
[3] E. Wigner, Phys. Rev. 40, 749 (1932); J. H. Irving and R. W. Zwanzig, J. Chem. Phys. 19, 1173 (1951).
[4] This solution agrees with I. R. Senitzky, Phys. Rev. 119, 670 (1960).

EA10. Iteration-Variation Method for Wave Propagation Problems. W. J. BYATT AND G. P. DEVAULT, *Sandia Corporation.*—Given a medium in which the index of refraction varies in one space coordinate only, transform methods are convenient for reducing an inhomogeneous scalar wave equation to an ordinary differential equation in which the square of the space-dependent index of refraction appears explicitly. We discuss an iteration-variation method for obtaining approximate expressions for the dispersion relation within the medium. The ordinary differential equation is converted to an integral equation. The Neumann series approximation to the solution of the integral equation is begun by iteration. The radius of convergence of the Neumann approximation is then analytically continued by using the iterates as the basis for a trial function in a variational principle. The iteration-variation method will be discussed and illustrated by means of an example for which an exact dispersion relation is known. Using only a two-term trial function, it develops that the existence and zeroes of the first two modes are accurately predicted.

EA11. Lattice with a Pathological Vibrational Frequency Spectrum. ROBERT ZWANZIG AND ROBERT J. RUBIN, *National Bureau of Standards.*—The lattice is a rooted Cayley tree, generated from the root by N successive twofold branchings. With each point of the tree are associated a mass m and a position coordinate x_i. All end points are held fixed to $x_i=0$. The potential energy is $V=\frac{1}{2}\sum\kappa_{ij}(x_i-x_j)^2$, where $\kappa_{ij}=\kappa$ if i and j are connected neighbors, and $\kappa_{ij}=0$ otherwise. The allowed vibrational frequencies, in the limit of infinite N, are given by

$$\omega=(\kappa/m)^{\frac{1}{2}}(3-2\sqrt{2}\cos r\pi)^{\frac{1}{2}},$$

where r is any rational number between 0 and 1. That fraction of all normal modes having precisely the frequency ω is $\rho(\omega)=1/(2^q-1)$, where r is expressed as the ratio $r=p/q$ of relatively prime integers p and q. The frequency spectrum is dense within the interval $(3-2\sqrt{2})^{\frac{1}{2}}$, $(3+2\sqrt{2})^{\frac{1}{2}}$; and $\rho(\omega)$ is discontinuous at every ω for which it does not vanish.

EA12. Relation between Classical and Relativistic Mechanics. JOSEPH M. STEIN, *General Atomic* (introduced by David Rose).—The relativistic coordinate transformations for relative motion of origins exemplified by constant displacement, constant velocity and constant force are written in terms of spinor components for one space dimension. When these are expressed in terms of Lie finite continuous transformation groups, it is observed that the corresponding infinitesimal transformations are of the exact form of the classical transformations. When reduced to integral form and the moving origin expressed in terms of the stationary origin, a unique correspondence between classical and relativistic motion is obtained. In this form the classical motion takes on a greater significance than as an approximation of the relativistic motion. By treating the Lie transformation in operator form, the development is generalized for three dimensions. Assuming that the formalism can be extended to more complex motion, the trajectories are used to develop a Lagrangian system of mechanics. This approach can serve as a means for dealing with relativistic problems which are outside of the scope of the restricted theory of relativity and which lead to undue complexities when dealt with by methods of the general theory of relativity.

EA13. Second-Order Theory of Planetary Atmospheric Re-Entry. W. H. T. LOH, *Chance Vought Research Center.*—Fundamental equation of re-entry is not solvable analytically. Several first-order approximate solutions were presented recently. For ballistic-type re-entry without lift at large angles of inclination, Gazley,[1] Allen and Eggers,[2] and Chapman[3] solved the equation approximately by neglecting both gravity force and centrifugal force terms. For gliding type re-entry

with lift at small angles of inclination, Allen and Eggers[2] obtained a first-order approximation by neglecting two minor terms in the basic equation. For gliding type re-entry with lift at large angles of inclination, Loh[4] obtained a first-order approximation by neglecting a different minor term in the equation. Now by using the known results of the first-order theory of re-entry as first approximation, the basic equation is solved approximately without neglecting any minor terms. Therefore it is valid for both small and large angles of inclination. Analytical solutions obtained here are compared with exact numerical solutions. They are in excellent agreement.

[1] Carl Gazley, Rand Rept. P-955 (1957).
[2] Allen and Eggers, NACA TN 4046 (1957).
[3] D. R. Chapman, NACA TN 4276 (1958).
[4] W. H. T. Loh, J. Aero/Space Sci. 27, 10 (1960).

MONDAY AFTERNOON AT 1:30

Terrace Room, Mark Thomas Inn

(J. N. COOPER presiding)

Superconductivity, Helium

F1. Exchange Energy of a Pair of He^3 Atoms in an Elongated Potential Well.* EDWARD M. SAUNDERS,† *Stanford University.*—By calculating the exchange energy of an idealized model, and then applying a perturbation to represent the effects of neighbors, the exchange energy of solid He^3 is studied semiquantitatively. At zero temperature, because of the zero-point energy inherent in systems of weakly interacting particles of small mass, interparticle correlation plays an essential role in the exchange energy calculation. The problem of two atoms held in a volume of appropriate size by an ellipsoidal harmonic oscillator potential is considered, by using a two-particle separation of the wave function. The interparticle coordinate is introduced in a fashion similar to that described by Walsh and Borowitz.[1] The idealized system shows ferromagnetism. A first-order perturbation is applied to distort the model so as to include correlation effects of neighbors in the solid. The result is an antiferromagnetic alignment.

* Supported by the Office of Naval Research, the U. S. Naval Postgraduate School, and the U. S. Air Force, Office of Scientific Research.
† Lieutenant Commander, Civil Engineer Corps, U. S. Navy.
[1] P. Walsh and S. Borowitz, Phys. Rev. 119, 1274 (1960).

F2. Ions in Liquid Helium. C. G. KUPER, *University of Illinois* (introduced by David Pines).—It is shown that Atkins' electrostriction model gives reasonable values for the mobility of positive ions in liquid helium, above 1°K, but cannot account for the observed difference between the positive and negative ion mobilities. Arguments are advanced in support of the "bubble" model of a negative ion: The negative ion is believed to be a free electron in a cavity of ~12 A radius. The bubble model leads to a mobility in fair agreement with experiment.

F3. Magnetic Flux Quantization in a Superconducting Ring. J. E. MERCEREAU AND L. L. VANT-HULL, *California Institute of Technology.*—The quantization of magnetic flux trapped by a superconducting ring, as postulated by London,[1] has been subjected to experimental test. This postulate suggests that such trapped flux must occur in integral units of $\phi_0 = (hc/e) \simeq 4 \times 10^{-7}$ gauss cm^2. As a consequence the magnetic dipole moment due to such trapped flux must be discrete. This effect has been investigated by looking for a difference in the magnetic moment of a ring when switched between the normal and superconducting states. The moment in the normal state is zero and in the superconducting state proportional to the deviation of the ambient flux from $N\phi_0$. Switching was done thermally at 6 kc and the changing dipole moment detected by the voltage generated in pickup coils loosely coupled to the ring. The experiment was done in a 1-mm indium ring under conditions where the ambient flux ϕ was slowly and continuously varied between $\pm 20(hc/e)$. Quantization should exhibit itself as an amplitude modulation of the output signal, the signal going to zero whenever $\phi = N\phi_0$. Experimental results have shown no such quantization effects.

[1] F. London, *Superfluid* (John Wiley & Sons, New York, 1950), Vol. 1, p. 152.

F4. Analysis of Electron Tunneling Between Superconductors. SIDNEY SHAPIRO AND PETER F. STRONG, *Arthur D. Little, Inc.*—The detailed calculations of the tunneling current vs voltage characteristic of a metal-dielectric-superconducting metal sandwich offered by Nicol, Shapiro, and Smith[1] have been extended to the case where both metals are superconducting.[1,2] The general picture of this case put forth in reference 1 is confirmed; namely the occurrence of a negative resistance region in the characteristic and its use as a direct measure of the superconducting energy gap. In addition, the calculations reveal certain special features that are also in agreement with experiment. These are the existence of a symmetric cusplike peak in the current at the lower voltage limit of the negative resistance region and the existence of a finite current jump at the upper voltage limit. An analytic expression for the magnitude of the current jump in terms of the superconducting energy gaps has been obtained. When the values for the energy gaps measured from the negative resistance region are used in this expression, the calculated and measured values of the current jump are in good agreement.

[1] J. Nicol, S. Shapiro, and P. H. Smith, Phys. Rev. Letters 5, 461 (1960).
[2] I. Giaever, Phys. Rev. Letters 5, 464 (1960).

F5. Tunneling between the Superconducting Pairs Pb-Sn and Sn-In. PAUL H. SMITH, SIDNEY SHAPIRO, AND JOHN L. MILES, *Arthur D. Little, Inc.*—Observation of the tunneling current vs voltage characteristic of superconducting metal-dielectric-superconducting metal sandwiches[1] has been extended to the cases of Pb-Sn and Sn-In pairs. A barium stearate film is used as dielectric.[2] A symmetric cusplike current peak and a current jump are observed as predicted (cf. preceding abstract) at, respectively, the lower voltage and upper voltage limits of the negative resistance region for the Pb-Sn sandwich. Data are presented on the temperature dependence of the energy gap for superconducting tin films. Good agreement is obtained with the predictions of Bardeen, Cooper, and Schrieffer.[3]

[1] J. Nicol, S. Shapiro, and P. H. Smith, Phys. Rev. Letters 5, 461 (1961); I. Giaever, *ibid.* 5, 464 (1960).
[2] J. L. Miles and H. O. McMahon (to be published).
[3] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. 108, 1175 (1957).

F6. Radiative Recombination Lifetime of Electrons and Holes in Superconductors.* B. N. TAYLOR, D. N. LANGEN-

BERG, AND E. BURSTEIN, *University of Pennsylvania.*—The low-voltage tunneling through oxide barriers between two superconductors depends on the density of electrons and holes in their conduction and filled bands. The density of carriers can be increased by electrical and optical "injection" processes. The radiative and nonradiative mechanisms which limit the lifetime of the added carriers are (a) the recombination of electrons and holes across the energy gap and (b) the pairing of electrons in the conduction band and the corresponding pairing of holes in the filled band. The electron-hole radiative recombination lifetime, τ_{opt}, was estimated for lead ($E_G = 2.7 \times 10^{-3}$ev) using the theory of Roosbroeck and Shockley. The frequency dependence of $\eta^2 \kappa$ was obtained from the theoretical expressions of Mattis and Bardeen[1] for the complex conductivity. The density of thermally generated carriers was calculated from the B.C.S. theory and from the experimental estimate for the density of states at the Fermi surface in the normal state proposed by Gold.[2] The τ_{opt} at 2°K is calculated to be 0.4 sec and the recombination radiation spectrum is peaked at 2.9×10^{-3} ev.

* Supported in part by the U. S. Atomic Energy Commission.
[1] D. C. Mattis and J. Bardeen, Phys. Rev. 111, 412 (1958).
[2] A. V. Gold, Phil. Mag. 5, 70 (1960).

F7. Nuclear Resonance in Superconducting Vanadium.* RICHARD J. NOER AND W. D. KNIGHT, *University of California, Berkeley.*—The resonance of V^{51} has been observed in the superconducting metal down to a temperature of 1.5°K, and compared with the normal resonance above 4°K ($T_c = 5.1$°K). The sample consists of 0.2 g of vanadium in a $1 \times 1 \times 3$ cm stack of flat 900-A films which were evaporated onto 0.00025-in. Mylar sheets. The critical field was 2500 gauss at 4.2°K and >10 000 gauss at 3°K. The linewidth was 14 kc at all temperatures, and the intensity varied only according to the Boltzmann factor. The resonance frequency was observed to be the same in the normal and superconducting states, from which we may infer that the electron spin paramagnetism is not reduced in the superconductor by more than 10%, which is the experimental accuracy.

* Supported in part by the Office of Naval Research.

F8. Nuclear Spin Relaxation in Superconducting Al Alloys. Y. MASUDA, *I.B.M. Watson Laboratory.*—Extending previous measurements of nuclear spin relaxation time T_{1S} in superconducting Al[1-3] we have measured T_{1S} as a function of temperature for specimens of Al containing various low concentration of impurities.[4] The experimental data on Al alloy, which contained 0.055 atomic percent Zn, agree well with the theory assuming $r = 60$ and using the same energy gap $2\epsilon_0(0) = 3.25kT_c$ as that used in pure bulk Al ($r = 10$). Other data on the specimen containing 0.160 at. % Ge show that $r = 60$ and $2\epsilon_0(0) = 3.35kT_c$. If the parameter $\Delta(=\epsilon_0(0)/r)$ represents an anisotropy of the energy gap, the experimental data show that the anisotropy of the energy gap present in the pure Al may be washed out by the impurity scattering, and therefore the energy gap width will be nearly the same as predicted by BCS.[5] Size effect on T_{1S} also will be discussed.

[1] A. G. Redfield, Phys. Rev. Letters 3, 85 (1959).
[2] Y. Masuda and A. G. Redfield, Bull. Am. Phys. Soc. Ser. II, 5, 176 (1960).
[3] Y. Masuda and A. G. Redfield, *The Proceedings of the Seventh Conference on Low Temperature Physics* (University of Toronto, September, 1960).
[4] These alloys were kindly supplied by B. Serin of Rutgers University.
[5] P. W. Anderson, J. Phys. Chem. Solids 11, 26 (1959).

F9. Magnetic Field Dependence of the Thermal Conductivity of Superconducting Tin Films.* DONALD E. MORRIS AND M. TINKHAM, *University of California, Berkeley.*—We have measured the change in the thermal conductivity of superconducting tin films which is produced by application of a magnetic field parallel to the plane of the films. The thermal conductivity appears to increase as H^2 up to the vicinity of the critical field. It then changes to a field-independent value characteristic of the normal state at all higher field. For a 2500-A film, the quadratic change typically reaches 25% of the total change. The observed effect is insensitive to small tilts of the applied field out of the plane of the film. At temperatures of 1.2°, 1.7°, and 2.1°K, the effect is similar except for the usual dependence of H_c on temperature. The absolute magnitude of the quadratic effect is roughly the same for films between 700 and 2400 A thick, while application of the critical field produces a greater change for thicker films. This is consistent with the assumption that only the surface penetration region is affected by a subcritical field. Orientations of the induced persistent currents perpendicular and parallel to the direction of heat flow give similar results.

* Supported in part by the Office of Naval Research, the National Science Foundation, and the Alfred P. Sloan Foundation.

F10. Superconducting Transition Temperature of Isotopes of Ruthenium. T. H. GEBALLE AND B. T. MATTHIAS, *Bell Telephone Laboratories, Inc.*—Preliminary measurements of the critical temperature T_c of powdered samples of Ru^{99} and Ru^{104} indicate that the dependence of T_c upon mass is much less than the inverse one-half power. While the observed transition is broad, the curves for both isotopes lie considerably closer together than the 0.01° displacement which would be expected if T_c were proportional to $M^{-\frac{1}{2}}$. Further experiments for the purpose of sharpening the transition curves are being performed.

F11. Critical Temperature for Superconducting Alloys. C. CHIOU, D. QUINN, AND D. SERAPHIM, *I.B.M. Research Laboratory.*—An analytic expression involving two arbitrary constants is fitted to the variation of critical temperature with alloy concentration in primary solid solutions. The fit is good over both the low-concentration region where T_c decreases rapidly with concentration, and at higher concentration where often T_c increases well above the value for the pure solvent. The fit continues up to the limit of solid solution (in some cases up to 15 at. % solute). Both constants correlate qualitatively with the square of the difference in valence between solute and solvent and quantitatively with the change in reciprocal free path with solute concentration. The correlation is apparent for 15 different solid solutions with solvents In, Sn, and Al. As a result we have predicted and found Al-Mg and Al-Zn rich solid solutions to be superconducting at temperature above the critical temperature for pure Al. The effect for gallium in indium, previously an anomaly,[1] fits into this empiricism.

[1] E. A. Lynton, B. Serin, and M. Zucker, J. Phys. Chem. Solids 3, 165 (1957).

F12. Superconductivity in the $CuAl_2$(C16) Crystal Class. M. F. GENDRON AND R. E. JONES, *I.B.M. Yorktown Research Laboratory* (introduced by W. D. Ittner, III).—Several superconducting compounds have been found in the $CuAl_2$(C16) family indicating that this structure is among those favorable for the occurrence of superconductivity. The compounds were: $AuPb_2$[1] ($T_c = 4.42$°K), $PdPb_2$(2.95°K), $RhPb_2$(2.66°K) and $AgIn_2$(2.30–2.46°K). The latter is believed to be the first silver compound known to be superconducting. Other compounds of this family were also tested: $CuAl_2$ (not superconducting above 1.066°K), $CoSn_2$(1.12°K) and $MnSn_2$ (1.12°K). In addition, two compounds of the closely related $AuSn_4$ type were found to be superconducting: $AuSn_4$ ($\times T_c = 2.38$°K) and $PtPb_4$(2.80°K). The compounds $PtSn_4$ and $PdSn_4$ were not superconducting above 1.35°K. The experimental results were obtained using low field magnetic susceptibility measurements. Among the superconducting compounds the variation of superconducting transition tem-

perature is in qualitative agreement with the empirical rules of B. T. Matthias.[2]

[1] J. F. Allen, Phil. Mag. 16, 1005 (1933).
[2] B. T. Matthias, in *Progress in Low Temperature Physics*, edited by C. J. Gorter (North-Holland Publishing Company, Amsterdam, 1957), Vol. 2.

F13. Uniaxial Stresses and Their Effect on the Critical Temperature for Superconductivity in Tantalum, Indium, and Tin. D. SERAPHIM, *I.B.M. Research Laboratory.*—Galvanometric measurements of the critical field near T_c are made for single crystal and polycrystal wire specimens of tantalum, indium, and tin. Measurements at zero stress are made before and after each set of measurements at an applied tensile stress. Reversible and irreversible shifts in critical field are separable. For tantalum at low stresses the reversible shift in T_c with the hydrostatic component of tensile stress is equal in magnitude and opposite in sign to the pressure effect measured by Jennings and Swenson.[1] The same is true for indium. At higher stresses a large *reversible* nonlinear effect also appears for these metals. Preliminary measurements on tin specimens have shown only the linear effect.

[1] L. D. Jennings and C. A. Swenson, Phys. Rev. 112, 31 (1958).

F14. Superconducting Transition Temperature of Plastically Deformed Al.† WILLIAM JOINER AND BERNARD SERIN, *Rutgers University.*—Pure aluminum was deformed at room temperature by cold-rolling and by fatigue. The rolled specimens were decreased in thickness by 95% and were foils. The transition temperature T_c of such foils is less than that of an annealed rod. T_c can be increased and made to approach that of the rod by annealing at 250°C or higher. By judicious annealing, the dependence of T_c on the extra electrical resistivity due to deformation was determined. The decrease in T_c is identical with that produced by the resistivity of electropositive impurities.[1] Foils quenched from 600°C and held at room temperature before being measured show a similar decrease in T_c. However, T_c seems to increase for thick specimens which have been fatigued by bending for several million cycles. Recent electron microscope studies[2] have indicated that the dislocation arrangements produced by cold work differ from those produced in fatigue.

† Supported by the National Science Foundation and the U. S. Army Signal Supply Agency, Fort Monmouth, New Jersey.
[1] G. Chanin, E. A. Lynton, and B. Serin, Phys. Rev. 114, 719 (1959).
[2] R. L. Segall and P. G. Partridge, Phil. Mag. 4, 912 (1959).

F15. Effect of Plastic Deformation and Annealing Temperature on Superconducting Properties. J. J. HAUSER, *Bell Telephone Laboratories, Inc.* (introduced by B. W. Batterman).—Single and polycrystals of Nb and Re were deformed in tension at room temperature. The critical field was found in both cases to increase with deformation and in the case of Nb the increase was as large as 150%. The change in critical field is related to the increasing dislocation density accompanying plastic deformation. Annealing the plastically deformed sample restored the original critical field. The transition temperature in Nb was not affected either by the deformation or the annealing treatment. The critical field before deformation, however, increases if the original annealing temperature is decreased. This can be explained by a progressive degassing of the sample at the higher temperature. The transition temperature of Re was found to depend on the annealing temperature and in some cases on plastic deformation. A transition temperature as low as 1.368°K was observed. The transition temperature is higher, the higher the annealing temperature before plastic deformation. Plastic deformation does not affect the transition temperature when the transition is sharp. However, when the transition is broad, plastic deformation raises the transition temperature and sharpens the transition region. A possible explanation for these results can be given in terms of the equilibrium number of vacancies at the annealing temperature.

MONDAY AFTERNOON AT 2:00

400 Spanagel Hall

(J. S. SMART presiding)

Magnetism I

FA1. Irreducible Linked Cluster Expansion in the Ising Model of Ferromagnetism. F. ENGLERT* AND R. BROUT, *Cornell University.*—The expectation value $\langle 0_r \rangle$ of any r-body operator with $H = \sum_{ij} V_{ij} f_i^z f_j^z$ may be obtained as a linked cluster expansion in the following way: (a) Write $H = H_0 + H_{int}$ where $H_{int} = (H - H_0)$ and $H_0 = \Delta \sum_i f_i^z$; here Δ is fixed by the condition

$$\langle f_i^z \rangle = \langle f_i^z \rangle_0 \tag{1}$$

(b) Expand $\langle 0_r \rangle$ in powers of H_{int} and expand each correlation function between same-spin indexes into semi-invariants. The following linked cluster expansion results:

$$\langle 0_r \rangle = \sum_{n=0}^{\infty} \frac{(-1)^n}{n!} \beta^n \langle H_{int}^n 0_r \rangle_{0,L}, \tag{2}$$

where to each vertex corresponds a semi-invariant of f_i^z the order of which is equal to the number of lines (V_{ij} bonds) arriving at that vertex. It is possible to show that only irreducible linked graphs contribute to (2) as a consequence of semi-invariant properties and of the renormalization condition (1) which is equivalent to a variational principle in the free energy. The expansion (2) is then applied to the sum of ring graphs and the spherical model follows below as well as above the Curie point. The expansion (2) is easily generalized for the quantum mechanical theory (Heisenberg model) by introducing "time-ordered" products and the sum of rings of the transverse energy corresponds then to the spin-wave theory.

* On leave of absence from Universite Libre de Bruxelles.

FA2. Diagrammatic Expansion for the Ising Model with Arbitrary Spin and Range of Interaction.* GERALD HORWITZ AND HERBERT B. CALLEN, *University of Pennsylvania.*—A new, simple diagrammatic expansion is developed for the free energy of the Ising model with arbitrary spin and range of interaction. The contribution of each diagram is a product of (1) the reciprocal of the order of the symmetry group of the diagram, (2) a product of semi-invariants for each spin in the diagram, the order equaling the number of bonds joined to that spin, and (3) a sum of products of exchange integrals without restrictions on the summation indexes (i.e., no "excluded volume" corrections). The expansion variables are the spin deviation operators $\sigma_i = \bar{S} - S_{iz}$ and $\bar{S}$ is chosen to eliminate a large class of diagrams; this choice of $\bar{S}$ also minimizes the corresponding free energy contribution, and implies $\bar{S} = \langle S_z \rangle$.

By further renormalization of the vertexes all reducible diagrams are eliminated. To zero order the molecular field solution is obtained. The next approximation consists of the summation of simple loop diagrams (justified near T_c by a modification of Brout's high-density criterion, and at low T by the decrease in magnitude of higher order semi-invariants). For nearest-neighbor interactions the specific heat is continuous, with an infinite slope on the low-temperature side of the transition.

* Supported by the Office of Naval Research.

FA3. Diagrammatic Expansion for the Heisenberg Ferromagnet with Arbitrary Spin and Range of Interaction.* HERBERT B. CALLEN AND GERALD HORWITZ, *University of Pennsylvania.*—The expansion developed for the Ising model, as given in the preceding abstract, is extended to the Heisenberg model of a ferromagnet. The additional spin-flip terms in the Heisenberg Hamiltonian contribute nothing to the free energy in zero order, and in this order the molecular field solution is retained. The first corrections contributed by the spin-flip loops consist of single spin-flip loops, added, of course, to the Ising-type diagrams. The vertexes are renormalized as in the Ising expansion, thereby retaining the self-consistent properties of the quantity $\bar{S}$. The solution to first order reduces at low temperatures to the spin-wave solution, differing from the elementary spin-wave solution only by exponential temperature factors, in agreement with Dyson. The renormalization of the vertexes explicitly evaluates Dyson's kinematical interaction, whereas the dynamical interaction is higher order in our expansion. The spin-flip operators make small (but non-negligible) contributions to the behavior in the vicinity of the Curie temperature. The method consequently provides a convenient and consistent solution in the entire temperature range.

* Supported by the Office of Naval Research.

FA4. Ferro- and Antiferromagnetism for Spin 1. G. F. DRESSELHAUS, *Lincoln Laboratory.**—An assembly of N atoms is considered in which each atom has spin 1 and is described by a nondegenerate spatial function. It is shown that, provided the Hamiltonian does not involve spin, the $(2N+1)$ states for which $S=N$ have the same energy as that $S=0$ state which is represented by (N is assumed even)

$$(000\cdots)-\frac{1}{(N-1)}\{(+-00\cdots)\}+\frac{1\cdot 2}{(N-1)(N-3)}\times\{(++--00\cdots)\}+\cdots+(-1)^{\frac{1}{2}N}\times\frac{(\frac{1}{2}N)!}{(N-1)(N-3)\cdots 1}\{(++\cdots--\cdots)\},$$

in which the curly bracket indicates that one takes all the permutations of the spin function. The $S=N$ state is the ferromagnetic state, while this particular $S=0$ state (one of many $S=0$ states) is an antiferromagnetic state.

* Operated with support from the U. S. Army Navy, and Air Force.

FA5. Antiferromagnetic Ground State. LAURA M. ROTH, *Lincoln Laboratory.*—A perturbation method is used to obtain the ground state energy of a system of spins characterized by the isotropic spin Hamiltonian, $2J\sum \mathbf{S}_i{}^A\cdot\mathbf{S}_j{}^B\Delta_{ij}$, where $J>0$, i and j run over the sublattices A and B, respectively, and Δ_{ij} is one if i and j are nearest neighbors and zero otherwise. The unperturbed Hamiltonian is taken to be $(2JZ/N)\mathbf{S}_A\cdot\mathbf{S}_B$, where S_A and S_B are the total sublattice spins, with the rest of the Hamiltonian treated as a perturbation. The unperturbed ground state is that in which each sublattice is in a state of maximum multiplicity ($S_A=S_B=NS$) and the two large spins are then put into a singlet state. The next unperturbed singlet is removed from this one by an energy $4JZS$, so that a perturbation scheme is feasible. A difficulty with this scheme is that a linked-cluster expansion cannot be used, but in each order one must evaluate the energy shift for arbitrary N and then take the limit as $N\to\infty$. This has been done to fourth order. The result is not quite identical with that obtained by Davis using the Néel state as the unperturbed ground state. Some interesting results are obtained by examining excited states: (1) The unperturbed system in its ground state would appear to be ordered in a neutron diffraction experiment in which a nearly elastic transition is made to a triplet state $2JZ/N$ away. (2) Among the triplet states is a group which appear to be spin waves.

* Operated with support from the U. S. Army, Navy, and Air Force.

FA6. Antiferromagnetic Contribution to the Polarization of Free Electrons by Inner Shell Spins. P. W. ANDERSON AND A. M. CLOGSTON, *Bell Telephone Laboratories, Inc.*—It is known that one contribution to the spin polarization of free "s" electrons by d or f electron spins in the transition group metals is an admixture of s electron functions into the inner shell function and vice versa. Although this effect is not present in free atoms, it exists in solids, and it is probably responsible for some of the binding energy of the iron group metals, in which the relevant matrix elements may be of the order of a few electron volts. This implies a rather large free electron polarization. We show that there is also an antiferromagnetic polarization effect caused by this covalent mixing of the d and s functions. The reason is that the filled level of one spin (say up) is full and therefore lies below the Fermi level, causing the electrons near the Fermi level to mix with it in an antibonding way and raising their energies. The inner shell level of the other spin is empty, and therefore above the Fermi level (because of the repulsive correlation energy with the inner shell electron of up spin), so that the free electron levels of down spin are lowered. The resulting polarization is negative.

FA7. Compensation of Ferromagnetic and Antiferromagnetic Contributions of Covalent Admixture in the Polarization of Free Electrons by Inner Shell Spins. A. M. CLOGSTON AND P. W. ANDERSON, *Bell Telephone Laboratories, Inc.*—We show now that the ferromagnetic polarization of s electrons caused by admixture with a localized inner shell level is almost precisely canceled, in a space average and in lowest order of perturbation theory, by the antiferromagnetic polarization effect mentioned in the preceding abstract. The total admixture is given by (for parallel spins as an example)

$$\sum_{k>k_F}\frac{(V_{kd})^2}{(\epsilon_k-E_d)^2}\simeq\frac{dn}{d\epsilon}\frac{\langle V_{kd}\rangle^2}{E_d},$$

where E_d is the position of the localized level below the Fermi surface and V_{kd} is the matrix element causing admixture. The approximation is fairly good even when $dn/d\epsilon$ is not constant. The polarization effect is

$$-(\text{energy shift})\times\frac{dn}{d\epsilon}=-\frac{(V_{kd})^2}{E_d}\frac{dn}{d\epsilon}.$$

The radial dependence of the two polarization effects is rather different, however; the polarization effect has a Ruderman-Kittel oscillatory shape, while the admixture is somewhat shorter range and always positive. The presence of this compensation may be important to the observed large negative values of hyperfine fields in magnetic metals, since it leaves only the true exchange polarization of the $4s$ electrons as a positive contribution from the outer electrons. At the same time, the accompanying decrease of the total d-shell magnetization may be a major effect in the iron group.

FA8. Theory of Nuclear Relaxation in Ferromagnetic Metals.* M. WEGER, A. M. PORTIS, AND H. SUHL, *University of California, Berkeley.*—The observed longitudinal nuclear relaxation time in the ferromagnetic metals, Fe, Ni, and Co, are between one and two orders of magnitude shorter than expected from the Korringa theory. The spin-spin coupling is also stronger, especially in Ni, than expected from the Suhl-Nakamura theory of nuclear spin coupling through spin waves. We have developed a theory of the longitudinal relaxation, which combines the Korringa and Suhl-Nakamura theories. This theory gives nuclear-electron coupling with a range of the order of a domain wall thickness rather than the short-range contact interaction of the Korringa theory. For weak *s-d* exchange coupling, the relaxation rate is proportional to the square of the exchange. For strong coupling the relaxation rate is independent of the strength of the coupling because of the large momentum transfer associated with a conduction electron spin flip. This theory gives reasonable agreement with experiment for Fe and Co in the strong coupling limit. It fails to account for the rapid relaxation in Ni, however. The transverse problem is more complex. A coupling between nuclei which involves both conduction electron and spin wave excitation seems indicated.

* Supported by the Office of Naval Research and the U. S. Atomic Energy Commission.

FA9. Nuclear Resonance of Co^{59} in Alloys. RICHARD CONLEY LA FORCE, S. FREDERICK RAVITZ, AND GENE F. DAY, *University of California, Berkeley.*—We have studied the effect of dilute solid solutions of iron and of nickel on the nuclear resonance of Co^{59}. We observe four lines in pure cobalt other than the principal resonance from nuclei in the fcc phase at 213.1 Mc. From their attenuation upon the addition of iron, which tends to stabilize the fcc phase, we identify three lines (210, 215.6, and 218.5 Mc/sec) as arising from the interaction of nuclei in the fcc phase with stacking faults and the fourth (223.1 Mc/sec) as due to nuclei in the hexagonal phase. The addition of iron, moreover, produces three new lines at 215.6, 214.2, and 210.1 Mc/sec. In the dilute nickel solutions the situation is much the same with respect to stacking fault and hexagonal phase lines. There are, however, four lines due to the presence of nickel (205, 209.5, 211.1, and 211.8 Mc/sec), all shifted to frequencies lower than the pure cobalt resonance frequency. These results will be discussed in terms of a nearest-neighbor exchange interaction together with a spatially periodic spin polarization about the impurity atom due to conduction electron scattering. The temperature dependence of the alloy resonances will also be presented.

FA10. Low-Temperature Magnetization of Nickel. B. E. ARGYLE AND E. W. PUGH, *I.B.M. Research Center.*—A new pyromagnetic technique, as described elsewhere,[1] has been used to measure the temperature dependence of the magnetization of single crystal nickel spheres from 4.2° to 60°K. The sensitivity of the apparatus currently permits the detection of changes in magnetization near 4.2°K of 3 parts in 10^6. The magnetization has been found to decrease monotonically with increasing temperature for samples magnetized parallel to the [111] or [100] directions. In fields large enough to align the magnetic moment parallel to the field, the variation of magnetization with temperature can be represented approximately by a T^n dependence, where n, in general, is closer to 1.6 than the 1.5 value predicted by the first-order spin wave calculation. This deviation from the $T^{1.5}$ law, as well as more drastic deviations at lower fields, is determined by crystallographic orientation and by the effective internal field. Recent modifications to the low-temperature spin wave calculations[2] will be combined with considerations of crystallographic misalignment in an attempt to explain these results.

[1] E. W. Pugh and B. E. Argyle, Sixth Annual AIEE-AIP Conference on Magnetism and Magnetic Materials, New York, November, 1960); J. Appl. Phys. (to be published).
[2] S. H. Charap, Phys. Rev. 119, 1538 (1960).

FA11. Magnetization in Thin Nickel Films. K. H. ROSETTE AND R. W. HOFFMAN, *Case Institute of Technology.*—The temperature dependence of magnetization in thin nickel films was measured by the torsion method.[1] Films were deposited at pressures less than 1×10^{-6} mm Hg onto glass substrates held at 75°C and were covered with SiO, then annealed at 275°C for 10 hr. Torque measurements were made in a separate magnetometer at a pressure of 10^{-3} mm Hg for a temperature range from 77° to 600°K. A 250-A film displayed bulk behavior. Thinner films displayed a smooth decrease of Curie temperature with decreasing thickness, in agreement with 60-cps hysteresis loop tracer measurements.[2] The lowest observed Curie temperature was 340°K, for a 16-A film. The oxide behavior observed in similarly prepared thin iron films[3] was not present.

[1] C. A. Neugebauer, Phys. Rev. 116, 1441 (1959).
[2] E. C. Crittenden, Jr., and R. W. Hoffman, Revs. Modern Phys. 25, 310 (1953).
[3] K. H. Rosette and R. W. Hoffman, *Structure and Properties of Thin Films* (John Wiley & Sons, Inc., New York, 1959), pp. 370–377.

FA12. Unusual Magnetic Structure of Face-Centered Cubic Fe. K. J. TAUER AND R. J. WEISS, *Ordnance Materials Research Office, Watertown, Massachusetts.*—Experimental evidence indicates that fcc Fe exists in two electronic configurations. At 0°K it is antiferromagnetic with the spins ($\mu_B\cong0.4$) probably alternating in and normal to (100) sheets. The second electronic configuration, approximately 0.03 ev higher with $\mu_B\cong2.7$, is thermally excited near room temperature. In the stable range of fcc Fe ($T>910$°C) the population of the upper level is about 75% due to its higher degeneracy. The coupling between atoms in the upper level is ferromagnetic, and alloying with fcc elements to the right (Co, Ni, Pt, Pd) reverses the order of the levels ($\mu_B=2.5$ lower) while alloying with fcc Mn further stabilizes the $\mu_B=0.4$ level. The evidence for these two electronic configurations comes from (1) neutron diffraction of fcc Fe Mn alloys, (2) the entropy of fcc Fe, (3) low temperature susceptibility of fcc Fe stabilized in Cu, (4) neutron diffraction of fcc Fe at $T\cong920$°C, (5) susceptibility of fcc Fe at $T>910$°C, (6) magnetic contribution to the resistivity of fcc Fe at $T>910$°C, and (7) thermodynamic reconstitution of the free energy of fcc Fe from Fe-Ni alloys. The two states probably involve the flipping of one 3*d* spin, indicating competition between intra-atomic exchange and interatomic cohesion.

FA13. Distribution of the Magnetization in a Ferromagnet. M. W. MULLER, *Varian Associates.*—The distribution of the magnetization is calculated for a thick ferromagnetic slab with easy axis transverse to the plane of the slab in a large applied field in the plane of the slab. The calculation predicts a stable nonuniform distribution which has several features suggestive of the domain pattern to be expected in such a system. In particular, the pattern consists of alternating strips having approximately the periodicity expected from conventional domain theory; incipient flux closure domains appear if the anisotropy field is smaller than the demagnetizing field.

FA14. Perturbation Theory of Cavities. R. F. SOOHOO, *Lincoln Laboratory.**—An nth-order perturbation theory of cavities analogous to the quantum mechanical one is developed. The results of the theory enable us to calculate, in a systematic way, the perturbing effects of the perturber in magnetic resonance experiments. In particular, by means of the perturbation formulas, we may calculate, step by step,

the change in the stored energy of the cavity and the electromagnetic field within and near the perturber to any degree of accuracy we desire. When the size of the perturber is sufficiently small, our result may be approximated by the first-order calculation which can be shown to correspond to the widely used Bethe-Schwinger perturbation formula.[1] Furthermore, the size and wall effects in ferromagnetic resonance studies comes out as a natural consequence of our calculation. The convergence of the nth order perturbation series and the degenerate cases will also be briefly discussed.

* Operated with support from the U. S. Army, Navy, and Air Force.

[1] H. A. Bethe and J. Schwinger, N.D.R.C. Report DI-117 (March, 1945); R. F. Soohoo, *Theory and Application of Ferrites* (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1960), p. 260–266.

MONDAY AFTERNOON AT 2:00

King Hall

(R. J. MAURER presiding)

DSSP Symposium on Atomic Properties

G1. Effects of Imperfections on the Vibrational Spectrum. H. B. ROSENSTOCK, *U. S. Naval Research Laboratory.* (30 min.)

G2. Interatomic Forces in Crystals from Neutron Scattering. B. N. BROCKHOUSE, *Atomic Energy of Canada.* (30 min.)

G3. Thermal Conductivity by Lattice Waves. PAUL G. KLEMENS, *Westinghouse Research Laboratories.* (30 min.)

G4. Diffusion in Solids. DAVID LAZARUS, *University of Illinois.* (30 min.)

TUESDAY MORNING AT 9:30

421 Spanagel Hall

(JOHN D. FERRY presiding)

High-Polymer Physics. I

Invited Papers

GA1. Polymer Relaxation. Y. H. PAO, *du Pont Experimental Station.* (30 min.)

GA2. Non-Newtonian Viscosity of Polymers. R. S. PORTER, *California Research Corporation.* (30 min.)

Contributed Papers

GA3. Dynamic Mechanical Properties of Polymers. DONALD G. LEGRAND, *General Electric Research Laboratory.*—During the past twenty years, a large number of instruments have been developed to study the dynamic mechanical properties of polymers for study in the solid state and in solution. While each of these instruments offers certain advantages, in order to investigate a phenomena which has been described extensively in the literature, commonly called the Fitzgerald effect, a new instrument has been built and tested. The instrument is limited in its low-frequency range by the transducer used. The high-frequency range is obtained by replacing certain critical components in the instrument. The useful range of the instrument is from 120 to 4000 cps in a temperature range of −20 to 120°C. The mechanical impedance of the material is measured in terms of a complex electrical response which is translated into a complex shear modulus. With the present measuring technique, the maximum precision obtainable is 5%. Results are presented for polyisobutylene, plasticized polyvinyl chloride, a crosslinked epoxy and polytetrafluoroethylene and compared with data from the literature.

GA4. Internal Friction in Stereoregular Polymethyl Methacrylate. W. G. GALL AND N. G. MCCRUM, *du Pont Experimental Station.*—The temperature dependence of the internal friction of stereoregular forms of polymethyl methacrylate (PMMA) has been determined at frequencies ca. 1 cps. Isotactic PMMA does not exhibit a side chain relaxation: its main chain relaxation is 66°C lower than that of conventional PMMA. Syndiotactic PMMA exhibits exactly the same relaxations as conventional PMMA. Since the density and infrared absorption spectra of syndiotactic and conventional PMMA are also comparable and differ from the isotactic form, it is concluded that conventional radical-initiated polymer is not truly atactic but has considerable syndiotactic character.

GA5. Dynamic Mechanical Properties of Natural Rubber.* EDWIN R. FITZGERALD, *The Pennsylvania State University* AND EDWARD J. COOK, *Chesapeake Instrument Corporation.*—The complex shear compliance ($J^* = J' - J''$) of several lightly vulcanized natural rubber (hevea) stocks has been measured over the frequency range 50 to 5000 cps and at temperatures from −50 to 80°C. The dynamic shear compliance at room temperature (~25°C) has also been obtained as a function of static elongation from 0 to 500%. In this case the general level of the storage compliance (J') from 50 to 5000 cps at first rises with elongation and then drops as the small-amplitude dynamic compliance measurements apparently reflect the reciprocal slope of the static stress-strain curve for natural rubber. Thus at 200% elongation the general level of the

storage compliance is about twice that at 0% elongation whereas at 300% elongation the level of storage compliance drops to approximately two-thirds the unstretched value. The results, both at low temperatures and at high elongations, are also correlated with known changes in crystallinity under these conditions. All measurements were made in a Fitzgerald apparatus which was modified to allow static elongation of the sample during dynamic tests at room temperature.

* This work was supported in part by the Office of Naval Research (Acoustics Branch).

GA6. Dynamic Compressibility of Polyvinylacetate and Its Relation to Free Volume. JOHN E. MCKINNEY AND HARRIET V. BELCHER, *National Bureau of Standards* (introduced by Robert S. Marvin).—The dynamic compressibility of a commercial polyvinylacetate was measured with varying static pressure (0–1000 bars), temperature (0–100°C), and frequency (50–1000 cps) utilizing piezoelectric volume expander transducers.[1] An inflection in the real part of the compressibility ($B^* = B' - iB''$) with a corresponding maximum in the imaginary part was observed when plotted as a function of temperature. The effect of increasing the static pressure or frequency was to shift the position of B_{max}'' to higher temperatures. The data can be represented by either reduced frequency or reduced temperature plots assuming viscosity proportional to exp $(1/\varphi)$ where $\varphi = \varphi_g + \alpha(T - T_g) - \beta P$ is a fractional free volume and T_g the glass temperature. The value of $\beta/\alpha = .024$°C bar arrived at from taking the shift in the temperature of B_{max}'' with pressure for constant frequency is in reasonable agreement with that calculated from compressibility and thermal expansivity data, assuming that β is the difference in the compressibilities and α the difference in thermal expansivities between the rubbery and glassy states. This same value of β/α has also been found for polyisobutylene, and natural rubber.

[1] J. E. McKinney, S. Edelman, and R. S. Marvin, J. Appl. Phys. **27**, 425 (1956).

GA7. Dynamic Mechanical Properties of Dilute Viscoelastic Solutions and Gels. MEYER H. BIRNBOIM AND JOHN D. FERRY, *University of Wisconsin.*—An apparatus has been developed to determine the components of the complex shear modulus of viscoelastic liquids and dilute gels over a continuous frequency range from 0.01 to 5 cps by amplitude-phase shift measurements and from 2.5 to 400 cps by transducer impedance measurements. The temperature range is from −40° to 150°C. The sample is deformed in very small strains with annular pumping geometry, as in the earlier apparatus of Smith, Ferry, and Schremp. Preliminary results on 2 to 3% solutions of polyvinyl chloride in di-2-ethyl hexyl phthalate provide the dynamic moduli and compliances and the relaxation and retardation spectra as they change during the process of gelation. The data are interpreted in terms of the theories of Rouse and Zimm.

GA8. Monte Carlo Method for the Study of the Dynamics of Polymers in Dilute Solution.* PETER H. VERDIER,† *M.I.T. and Union Carbide Research Institute,* AND W. H. STOCKMAYER, *M.I.T.*—A program is described which simulates on a digital computer the dynamical behavior of a lattice-model polymer in dilute solution. Both steady state and relaxation phenomena may be studied with the program. In a preliminary investigation of the method, we have studied the relaxation and equilibrium distribution of the end-to-end length of chains of 8, 16, 32 and 64 beads. The equilibrium dimensions agree well with the calculations of Wall and his collaborators,[1] while the relaxation times are close to those predicted from the hydrodynamic theory of Rouse and Zimm.[2]

* Supported in part by the Office of Ordnance Research.
† Present address: Union Carbide Research Institute, P.O. Box 324, Tuxedo, New York.
[1] F. T. Wall, L. A. Hiller and W. F. Atchison, J. Chem. Phys. **23**, 2314 (1955).
[2] B. H. Zimm, J. Chem. Phys. **24**, 269 (1956).

GA9. Extension of the Eyring-Ree Viscosity Theory. J. A. FAUCHER, *Union Carbide Chemicals Company.*—The Eyring-Ree theory of non-Newtonian viscosity postulates discrete groups of flow units with widely different relaxation times. With suitable assumptions the "generalized flow equation", which is a finite sum over all flow units, can be extended to the case of a continuous distribution of flow units. This converts the flow equation to an integral equation of the form

$$\tau(\dot{\gamma}) = \int_0^\infty f(t) \operatorname{arc\,sinh} \dot{\gamma} t \, dt.$$

Given $\tau(\dot{\gamma})$ this equation can be solved by the use of Hankel and Laplace transforms to yield $f(t)$, the distribution of relaxation times. Some original data for the flow of molten polyethylene are discussed from this point of view.

GA10. Glass Transition Temperatures of Vinyl Polymers. F. P. REDING, *Union Carbide Chemicals Company.*—In first approximation the glass transition temperature *Tg* of many random vinyl copolymers is a linear function of the composition along the line drawn between the *Tg* of the respective homopolymers. It is now well established that *Tg* for linear polyethylene is about −125°C and thus it might be expected that *Tg* for ethylene copolymers should fall along the line drawn between −125°C and the *Tg* of the homopolymer of the other monomer. However, upon investigating copolymers of ethylene with a variety of other monomers, it is found that the *Tg* of the copolymer is lowered to −20°C but then remains constant with the addition of more ethylene. This result suggests −20°C is a transition characteristic of the substituted alkyl chain. The *Tg*'s of a number of vinyl homopolymers are discussed from this point of view.

TUESDAY MORNING AT 9:15

King Hall

(L. R. MAXWELL presiding)

DSSP Invited Papers

H1. Absorption and Fluorescence Spectra of Rare Earth Salts and Their Magnetic Properties. G. H. DIEKE, *Johns Hopkins University.* (30 min.)

H2. Theory of Random Dilute Ferromagnets. R. J. ELLIOTT, *University of California, Berkeley.* (30 min.)

TUESDAY MORNING AT 11:00

King Hall

(J. H. VAN VLECK presiding)

Oliver E. Buckley Lecture

H3. Some Recent Developments in Electron Theory of Solids. W. KOHN, *University of California, La Jolla.* (45 min.)

Business Meeting of the Division of Solid State Physics

TUESDAY MORNING AT 9:30

Copper Cup Room, Herrmann Hall

(W. P. CUNNINGHAM presiding)

Graphites

HA1. Magnetic Susceptibility of Pyrolytic Graphite. T. B. SMITH AND D. B. FISCHBACH, *Jet Propulsion Laboratory,* C.I.T.*—The diamagnetic susceptibility of pyrolytic graphite has been measured at room temperature by the Faraday method as a function of heat treatment temperature. Both the susceptibility perpendicular ($\chi_\perp$) and parallel ($\chi_\parallel$) to the plane of the deposit have been measured. For graphite deposited in the range 2000° to 2200°C, $\chi_\perp$ is approximately equal to χ_c, the c-axis susceptibility of natural single crystals, but the anisotropy ratio, $\chi_\perp/\chi_\parallel$, is much lower. No change occurs on heat treatment up to ~2400°C. On heating above this temperature $\chi_\perp$ decreases, reaching a minimum value about 30% lower than the initial value near 2800°C, and then increases again. $\chi_\perp/\chi_\parallel$ increases monotonically. Differences in $\chi_\perp$ of up to 15% between top and substrate portions of the as-deposited material have been observed in some cases. These differences disappear with heat treatment. The changes in susceptibility with heat treatment are associated with extensive changes in other physical properties and result from a sort of recrystallization. The relationship of the susceptibility behavior to the concurrent structural changes will be discussed.

* A contract facility of the National Aeronautics and Space Administration.

HA2. Effect of Boron Doping on the Diamagnetic Susceptibility of Graphite.* D. E. SOULE AND C. W. NEZBEDA, *National Carbon Company.*—Measurements by the Faraday method have been made on polycrystalline AGK-SP graphite samples at 300°K to determine the susceptibility variation with boron acceptor concentration from ~0.02 to 1500 ppm. Three orthogonal components were determined for each cube as a function of magnetic field from 9 to 20 kgauss to correct for ferromagnetic impurities by the Honda-Owen method. The total susceptibility trace χ_T is invariant to a single crystal-to-"ideal" polycrystal transition even for the anisotropic case.[1] Assuming $\chi_\perp = -0.5\times10^{-6}$ emu/g for the isotropic boron-insensitive core or basal plane component,[2] then $\chi_T = \chi_\parallel + 2\chi_\perp = \chi_\parallel + 1.0\times10^{-6}$ emu/g where $\chi_\parallel$ is the single crystal component parallel to the hexagonal axis. The conduction carrier contribution, $\chi_\parallel - \chi_\perp$, can thus be inferred from these results on polycrystalline graphite. Its normalized value was observed to change with increasing boron content from -21×10^{-6} emu/g to -6.1×10^{-6} emu/g, presenting a broad shoulder about an atom ratio of 5×10^{-4} B/C. This behavior agrees substantially with the theoretical dependence versus the excess hole concentration.[3]

* This work was supported in part by a U. S. Air Force contract.

[1] W. P. Eatherly and J. D. McClelland, Phys. Rev. 89, 661 (1953).

[2] N. Ganguli and K. S. Krishnan, Proc. Roy. Soc. (London) 177A, 168 (1941).

[3] J. W. McClure, Phys. Rev. 119, 606 (1960).

HA3. Electrical Properties and Structural Parameters of Pyrolytic Graphites. W. DETER STRAUB AND CLAUDE A. KLEIN, *Raytheon Company.*—The electrical properties of artificial graphites are known to be determined by the crystalline structure. In order to identify the role of structural factors in PG, a series of specimens deposited at $1600° < T_d < 2600°$C has been examined in some detail. Basal plane and c direction resistivities are both strongly dependent on T_d; specimens prepared at 2500°C have a room-temperature $\rho_a \approx 2\times10^{-4}$ ohm-cm, a corresponding $\rho_c \approx 0.5$ ohm-cm, and thus exhibit electrical anisotropies of the order of 2.5×10^3. The temperature dependence of ρ_a, which reproduces the behavior of the usual synthetic graphites, appears to be essentially a matter of crystallite size and layer order. The temperature coefficient of ρ_c, though negligible for $T<77$°K, remains always negative and intimates the presence of fixed scattering centers along the c direction. With a magnetic field applied across the deposit, the Hall coefficient reflects the morphological perfection strictly in terms of layer order: Turbostratic specimens are p-type, whereas graphitized specimens have small negative R_H characteristic of single crystals. The quadratic low-field dependence of the transverse magnetoresistance alters at higher fields to a $H^{1.7\pm}$ dependence in all our specimens, but the magnitude of $\Delta\rho/\rho_0$ is sensitive to the crystallites' alignment and increases rapidly with the degree of preferred orientation.

HA4. Isothermal Transport Processes in n-Type Pyrolytic Graphite. CLAUDE A. KLEIN, *Raytheon Company.*—The basal plane conductivity, Hall effect, and transverse magnetoresistivity data taken on ordered highly-oriented PG have been analyzed using a two-carrier model patterned upon the magnetoconductivity-tensor approach. The main conclusions are: (1) The intrinsic carrier concentration decreases almost linearly from 6.5×10^{18} cm^{-3} at 300°K to less than 2×10^{18} cm^{-3} at 4.2°K, in fair agreement with single-crystal results; (2) In the same temperature range the hole mobility of a 2500°C specimen increases from 2.1×10^3 to 4.0×10^3 cm^2/v-sec, the

mobility ratio μ_e/μ_h remaining practically equal to 1.1; (3) The ρ_a vs T dependence is compatible with crystallite sizes $L_a \approx 3L_{th}(T_{min})$, where $L_{th}(T_{min})$ represents the thermal mean free path at the temperature of the resistivity minimum, and thus indicates that $0.1 < L_a < 0.2\mu$. Moreover, it has been established that the mobility can be theoretically described by combining the temperature-independent electron-boundary scattering with an electron-phonon contribution proportional to the lattice specific heat which affects the electrical behavior of these materials already at $T = 77°K$. While these are gratifying conclusions, they do not allow us yet to infer correct results for the conduction at 4.2°K on the basis of the available galvanomagnetic data; further work is in progress.

HA5. Radiation Effects in Pyrolitic Graphite. C. E. KLABUNDE, T. H. BLEWITT, AND R. R. COLTMAN, *Oak Ridge National Laboratory.**—Earlier studies of the isochronal annealing of pyrolitic graphite following neutron bombardment at 15°K established that the resistivity was unaffected to 80°K. Higher temperature pulses resulted in an increase in resistivity with a maximum being reached following a 140°K pulse. This increase can be attributed to either a decrease in the carrier concentration or to an agglomeration of individual defects to form small clusters. The present experimental work studied the effects of annealing on the resistivity-dose curves at 4.2°K. It was found that despite the increase in resistivity the shape of the dose-resistivity curve was unaffected by a 140°K anneal. This is inconsistent with a change in the number of current carriers so that it can be inferred that an agglomeration of defects occurs. The shape of the dose-resistivity curve is, however, indicative that the number of current carriers changes during the bombardment. These two facts suggest a model where the interstitials produced by the bombardment become mobile at 80°K and agglomerate to form platelets apparently in the space between c planes.

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

HA6. Electron Spin Resonance in Neutron-Damaged Graphite. G. WAGONER, *National Carbon Company, Division of Union Carbide Corporation.*—The electron spin resonance of a series of neutron-irradiated single graphite crystals has been investigated. The results are in agreement with the observations of Hennig and Hove[1] that neutron damage introduces acceptors into graphite; however, their interpretation of the paramagnetic resonance requires modification. Observation of the charge carrier spin resonance[2] as a function of neutron irradiation shows that the g-shift anisotropy decreases from 0.047 for pure undamaged graphite to 0.010 for graphite which has undergone 25 Mwd/ton of neutron irradiation in the Hanford reactor. A similar decrease in anisotropy due to the introduction of acceptors is obtained upon boronation of graphite. Comparison of a number of neutron-damaged specimens with a series of boron doped single crystals yields a value of $(2.5 \pm 0.5) \times 10^{18}$ acceptors per cm³ per Mwd/ton of irradiation. (1 Mwd/ton yields about 6×10^{16} neutrons per cm² with $E > 1$ Mev.) No new spin resonance is observed in the irradiated samples and the creation of unpaired spins in the earlier report[1] is more probably due to an enormous enhancement of the signal in polycrystalline graphite due to the g-shift reduction under irradiation.

[1] G. R. Hennig and J. E. Hove, *International Conference on Peaceful Uses of Atomic Energy* (United Nations, New York, 1956), Vol. 7, p. 666.
[2] G. Wagoner, Phys. Rev. 118, 647 (1960).

HA7. Ratio of Atomic Stopping Powers of Graphite and Diamond for 1.1-Mev Protons. SHELDON D. SOFTKY, *Stanford Research Institute.*—The theory describing energy loss of heavy charged particles in matter predicts that different physical or chemical forms of the same element will have slightly different stopping powers. Since two different forms of a pure element exhibit the same nuclear scattering cross section, it has been possible to measure the relative atomic stopping power of graphite and diamond by observing the yields of back-scattered protons from thick targets of these materials. The stopping power of graphite has been measured to be 1.0604 ± 0.0090 times that of diamond (for 1.1-Mev protons). Using the theoretical density of graphite, a calculation based on this result and Brandt's version of stopping theory yields the result that the molecular polarizability of graphite is 4.9 times that of diamond.

TUESDAY MORNING AT 9:30

Ballroom, Herrman Hall

(H. N. LEIFER presiding)

Galvanomagnetic Properties of Semiconductors

I1. Tube-Integral Calculation of Transport Coefficients for Electrons in Toroidal Energy Surfaces. R. C. CASELLA, *IBM, Yorktown Heights.*—The formal weak-field expansion, used previously[1] to obtain the (anisotropic) Hall coefficients in wurtzite assuming toroidal energy surfaces, leads to divergent results when applied to a calculation of the magnetoconductances. The difficulty results from the inappropriateness of expanding in powers of $\omega_c\tau$ (where ω_c is the cyclotron frequency and τ, the relaxation time) since ω_c is highly dispersive.[1] Integral expressions for the conductance coefficients $\sigma_{xy}(H_z)$ and $\sigma_{zz}(H_z)$($z \| c$ axis) associated with the Hall effect and transverse magnetoresistance, respectively, have been obtained by Shockley's tube-integral method,[2] which does not require assumptions regarding the strength of the magnetic field H_z. In a suitably redefined weak-field limit, the result for the Hall coefficient reduces to that obtained earlier.

[1] R. C. Casella, Phys. Rev. Letters 5, 371 (1960).
[2] W. Shockley, Phys. Rev. 79, 191 (1950).

I2. Strong Field Galvanomagnetic Effects in n-InSb.* W. F. LOVE AND JAMES C. HASLETT, *University of Colorado.*—Measurements of magnetoresistance and Hall effect in pulsed magnetic fields of 180 kgauss have been made on specimens of n-InSb in the temperature interval 30–300°K. In the extrinsic range of conduction (<100°K) both longitudinal and transverse magnetoresistance ratios $\rho(H)/\rho(0)$ vary with magnetic field and temperature as H/T at large magnetic fields. The longitudinal effects are an order of magnitude lower than transverse effects. Below 75 kgauss the longitudinal magnetoresistance shows an anomalous field dependence, exhibiting two "humps" superimposed on a linear variation with increasing magnetic field. These "humps" disappear at the upper and lower ends of the temperature interval studied. The Hall coefficient increases with increasing magnetic field in the intrinsic range. This effect will be interpreted in terms of an increase

of the band gap with magnetic field of the order of 19×10^{-4} ev/kgauss.

* Research supported by the U. S. Atomic Energy Commission.

I3. Galvanomagnetic Effects in *n*-Type GaSb.* W. M. BECKER AND H. Y. FAN, *Purdue University.*—Magnetoresistance, Hall effect, and conductivity were investigated for single crystals of *n*-type GaSb with Hall coefficients $R=-3$ to -70 cm³/coul at room temperature. Measurements were made at room temperature, 77°, and 4.2°K. Magnetoresistance was measured as a function of field orientation for a sample ($R=-4$) with $I\|\langle110\rangle$; it varied at all temperatures as $\sin^2(H,I)$ for H in the $(1\bar{1}2)$ plane, and the transverse magnetoresistance M_t was independent of field direction. Measurements on sample ($R=-4$) at room temperature and 77°K and on sample ($R=-3.2$) at 4.2°K showed that $M_t\propto H^2$ up to 14 000 oe. Room temperature values of $\Delta\rho/\rho_0H^2$ for the various samples were around $\sim2.5\times10^{-10}$ oe^{-2}. At the low temperatures, M_t of the samples of high-carrier concentrations increased by several times while, for the samples of the low-carrier concentrations, M_t became very small; the transition occured at $1/R\sim0.2$ cm³/coul. The behavior is consistent with a model of two conduction bands with an energy separation $\Delta E\gtrsim4\times10^{-3}$m/m* ev. With $m^*=0.047$m for the lower band, $\Delta E\gtrsim0.085$ ev. The magnetoresistance-field orientation data of sample ($R=-4$) indicates that the anisotropy factor K of the higher band is not very large.

* Work supported by a Signal Corps contract.

I4. Galvanomagnetic Effects in *p*-Type Silicon. E. ALLAN WILLIAMS,* *University of California, Santa Barbara,* AND H. Y. FAN, *Purdue University.*—Hall coefficient, resistivity, and magnetoresistance measurements have been made on high purity (6000 ohm-cm) *p*-type silicon at temperatures between 77° and 385°K. Bridge type samples were used with alloyed aluminum contacts. The current was in the 111 direction and Hall magnetic field was nearly in $1\bar{1}0$ direction. Magnetoresistance measurements were made at 77°K as a function of magnetic field and as a function of the field orientation in the $11\bar{2}$ plane. Above 120°K, $R/\rho=AT^{-\alpha}$ with $A=1.8\times10^{10}$ cm³/sec-v and $\alpha=3.1$; the value at 77°K ($R/\rho=15\,000$) was appreciably lower. The Hall coefficient ranged from (3.60 to 3.37)$\times10^6$ cm³/coul as H varied from 350 to 14 000 gauss at 77°, and between (2.38–2.47)$\times10^6$ in the range 400 to 24 000 gauss at room temperature. Some evidence of fine structure[1] was apparent at room temperature between 8000 and 18 000 gauss, while at 77° it was slight between 350 and 14 000 gauss. At 77°K, $\Delta\rho/\rho_BH^2$ varied from 8.8×10^5 to 2.5×10^7 cm⁴/v²-sec² for fields 300 to 14 000 gauss. The ratio of $\Delta\rho/\rho_0H^2$ for $H_\perp I$ to that for $H_\parallel I$ was 4.3 at 4000 gauss.

* Work done while on sabbatical leave at Purdue University; work was supported by a Signal Corps contract.
[1] A. C. Beer, J. Phys. Chem. Solids 8, 507 (1959).

I5. Galvanomagnetic Tensor for Pure Tellurium from 77° to 300°K. ALLEN NUSSBAUM AND ROBERT J. HAGER, *Honeywell Research Center, Hopkins, Minnesota.*—The elements of the galvanomagnetic tensor of pure, single crystal tellurium were measured from 77° to 300°K. This extends the work of Roth[1] and of Nussbaum and Long[2] by giving the temperature dependence of the following twelve elements: ρ_1, ρ_2, R_1, R_2, ρ_{1111}, ρ_{1133}, ρ_{1123}, ρ_{3333}, ρ_{3311}, ρ_{1313}, ρ_{1123}, and ρ_{3311}. The general behavior of our material, which is purer than Roth's, is about the same for the elements he measured. However, we find that ρ_{1123} and ρ_{2311} over the entire temperature range are essentially zero, and this value is consistent with the hypothesis of ellipsoidal energy surfaces. This result does not agree with that obtained for large crystals grown by the Bridgman method.[3]

[1] H. Roth, J. Phys. Chem. Solids 8, 525(1959); General Atomic Rept. GA-791 (San Diego, California), August 1960.
[2] A. Nussbaum and D. Long, International Semiconductor Conference, Prague, 1960 (to be published).
[3] Professor P. Aigrain (personal communication).

I6. Galvanomagnetic Properties of Grain Boundaries in Germanium from 2°–240°K. G. LANDWEHR AND P. HANDLER, *University of Illinois.*—Conductivity, reduced Hall-constant, and transverse magnetoresistance were measured as functions of temperature from 2–240°K for 20° tilt grain boundaries. At 4.2° and 80°K the field dependence of reduced Hall coefficient and transverse and longitudinal magnetoresistance were investigated, in addition to the angular dependence of the transverse effect. The properties of intrinsic and extrinsic *n*- and *p*-type samples were measured. The results for the *p*-type sample are only significant below 10°K when the bulk conductivity is frozen out. Regardless of the bulk resistivity the data above 40°K can be explained by assuming a narrow, degenerate *p*-type region in the inner parts of the grain boundary and the presence of a minority of nondegenerate holes in the outer wings. At low temperatures, for all samples at magnetic fields of 5000 oe, an increase of magnetoresistance proportional to $T^{-1.53}$ was observed. Qualitatively this can be explained with the presence of a very small number of nondegenerate holes with a very high mobility, which are scattered mainly by ionized impurities. The Hall mobility of the degenerate holes is 300 cm²/v sec at 4.2°K. Pronounced effects were observed in the angular dependence of the transverse magnetoresistance due to the small thickness of the boundary (about 50A) at all temperatures.

TUESDAY MORNING AT 9:30

Criscuolo Hall

(R. A. SATTEN presiding)

Charge Transport

IA1. Theory of the Ionic Hall Effect.* P. L. READ† AND E. KATZ, *University of Michigan.*—A simple theory of the Hall effect due to the motion of ionic charge carriers in a solid is presented. The theory predicts a small but finite Hall effect for each mobile species of ionic carrier present. The theory proceeds directly from a slightly refined version of the usual ionic mobility theory. This refined mobility theory takes into account the effect of an applied electric field on *both* the height of the energy barriers in possible jump directions *and* the number of approaches per second which a carrier makes toward these barriers. The latter effect is not considered in the usual mobility theory. The physical basis for the occurrence of a finite ionic Hall effect is apparent in the development of the theory. The theory was verified by ionic Hall effect measurements in NaCl.[1]

* Supported by the Office of Naval Research.
† Now at the General Electric Research Laboratory.
[1] P. L. Read and E. Katz, Phys. Rev. Letters 5, 466 (1960).

IA2. Search for a Hall Effect in an Organic Semiconductor. WENDELL S. WILLIAMS, *National Carbon Company*, AND JAN KOMMANDEUR, *Union Carbide Corporation*.—No observation of the Hall effect in a well-defined organic semiconductor has yet been reported. Kepler, *et al.* recently described some low-resistivity organic semiconductors but were unable to detect a Hall voltage. The question arises whether the signal is merely very small or absent for some fundamental reason. A measurement on a material with known carrier concentration, for which the Hall voltage can be predicted, is therefore instructive. In the present work a search was made for a Hall voltage in a complex of iodine with perylene. For this material Singer and Kommandeur have correlated the observed electron spin resonance intensity with the charge carrier density, obtaining $n=4.6\times10^{19}$ g^{-1} (9.2×10^{19} cm^{-3}). From the standard one-carrier formula, the expected Hall voltage for iodine-perylene is 0.05 μv at a current of 1.4 ma and a magnetic field of 5000 gauss for a sample thickness of 1 mm. With these parameters, in an experiment in which a 0.02 μv signal would have been detected, no Hall voltage was observed. From this negative result a minimum carrier concentration of $n\geq2.2\times10^{20}$ cm^{-3} would be inferred. This result further supports the theory that conduction in organic solids takes place by a localized process.

IA3. Electrical Conductivity Measurements in the System MgO-NiO.— MYRON O. DAVIES, *NASA, Lewis Research Center* (introduced by L. A. Girifalco).—As a part of research on transport phenomena in pure and doped magnesium oxide, it has been of interest to determine the electrical conductivity of various compositions in the MgO-NiO system. Polycrystalline compacts possessing densities of approximately 95% single crystal density have been prepared by the following procedure: mixing the dry powders, pressing hydrostatically to 50 000 psi, and firing to 1300°C in an argon atmosphere. The conductivity measurements have been made with a capacitance measuring assembly in a specially designed high-temperature inert atmosphere furnace. For the pure MgO, the conductivity is slightly more than one order of magnitude larger than literature data for single crystal MgO.[1] At temperatures above 1040°C the activation energy for conductivity is 3.3 ev. This activation energy decreases with the addition of NiO to the specimens, reaching 2.1 ev for the one containing 35.5% NiO.

[1] S. P. Mitoff, J. Chem. Phys. 31, 1261 (1959).

IA4. Time Dependent Ionic Polarization of NaCl Crystals.* P. H. SUTTER,† *Yale University*, AND A. S. NOWICK, *I.B.M. Research Center*.—It is widely believed that the time dependent polarization which occurs upon application of a dc field to alkali halide crystals is due to the blocking of ionic discharge at the electrodes, the quantitative theory for which was given by Jaffé.[1] Jaffé's equations are nonlinear and predict severe deviation from Ohm's law and failure of the superposition principle for ordinary values of applied potential. The present experimental work covers the range 25 to 200°C for "pure" NaCl crystals. The polarization is found to be structure sensitive, depending on annealing, cold working, and impurity content. It is consistently found, however, that Ohm's law and the superposition principle are obeyed. The temperature dependence of the polarization is studied and it is found that the polarization magnitude is approximately independent of temperature but that the process occurs more rapidly at higher temperatures in accord with an activation energy of about 1.1 ev. The following conclusions are drawn: (1) Polarization in this range is not related to electrode effects but originates in a time dependent volume polarization phenomenon. (2) The true ionic conductivity is that obtained from the final current, i.e., after the transient polarization processes have ceased.

* Supported in part by the U. S. Air Force Office of Scientific Research.
† Now at Westinghouse Research Laboratories.
[1] G. Jaffé, Ann. Physik 16, 217, 249 (1933).

IA5. Ionic Conductivity of Doped NaCl Crystals in the Association Region. R. W. DREYFUS AND A. S. NOWICK, *I.B.M. Research Center*.—Previous experimental results on the dc conductivity of NaCl crystals doped with divalent cation impurities, have indicated that the electrostatic dipole field of an associated impurity-vacancy pair may trap a second Na^+ vacancy. An expression derived for the concentration of free Na^+ vacancies in equilibrium with the above complexes predicts that the free vacancy concentration will be independent of impurity concentration at sufficiently low temperatures. This implication has been investigated by using the dc electrical conductivity as a measure of the free vacancy concentration in the temperature range from -10 to $+100$°C. NaCl crystals were prepared with divalent impurities such as Mg^{++}, Mn^{++}, Ca^{++}, and Sr^{++}. Different cooling rates in the 250 to 125°C range were used to alter the degree of impurity precipitation and, thereby, to change the concentration of isolated impurity ions in a particular sample. The experimental results indicate that the room temperature conductivity in doped samples is essentially independent of the degree of impurity precipitation, as predicted from the above theory. Nevertheless, below room temperature the electrical conductivity of slowly cooled samples is often found to be greater than that of quenched samples. The existence of other types of complexes, involving clusters of impurity ions, may explain this crossing over of conductivity curves.

IA6. Hall Mobility of Electrons in Pure Silver Chloride. TAIZO MASUMI AND FREDERICK C. BROWN, *University of Illinois*.—The Hall mobility of photoelectrons in crystals of AgCl was studied as a function of temperature down to 5°K using pulse techniques as previously reported.[1] Further measurements for samples of different preparation and purity have been made in an attempt to determine the factors which control electron scattering. Very high purity AgCl was prepared by zone refining in a halogen atmosphere starting with the central portions of previously zone refined ingots. A few crystals containing additions of certain heavy metal impurities were also investigated. The results show that electron mobility below 40°K is a sensitive function of crystal purity. Mobilities in excess of 2×10^4 cm^2/v-sec have been observed in the purest crystals whereas heavy metal additions in concentrations of the order of one part in 10^5 reduce the residual mobility to values below 3×10^3 cm^2/v-sec. Optical mode scattering is definitely observed above 40°K in the pure crystals, and, in fact, the Debye temperature associated with longitudinal optical vibrations can be deduced from the mobility experiments for comparison with Reststrahl data.

[1] K. Kobayashi and F. C. Brown, Phys. Rev. 113, 507 (1959).

IA7. Pipe Diffusion in Lithium Fluoride.* R. N. TUCKER AND A. L. LASKAR,† *University of Illinois* (introduced by R. Thomson).—Localized diffusion of sodium ions from a film of NaCl through LiF crystals in an electric field shows a dislocation dependence. Measurements were made over the temperature range 200° to 700° C with fields of 200 vdc/cm to 3000 vdc/cm, the electrode at the unplated surface being negative with respect to that at the plated surface. Initially the conduction current shows an ohmic rise with an associated activation energy of 0.74 ev. Simultaneously, microscopic dendrites of sodium grow from the cathode into the bulk of the crystal. Following a peak, the conduction decreases to a steady value, and the dendritic growth ceases. During the initial phase the amount of sodium transported shows a nearly 1:1 correspondence to the total charge. These phenomena do not occur when the cathode is placed on a dislocation-free area, nor when no field is applied, implying a pipe diffusion of sodium ions which are reduced at the cathode forming a dendritic extension into the crystal.

* Supported by the U. S. Air Force, Office of Scientific Research.
† Present address: *India Institute of Technology, Kharagpur.*

IA8. Self-Diffusion of Cl^{36} in TlCl. ROBERT J. FRIAUF, *University of Kansas.*—Previous measurements of ionic conductivity and of diffusion of thallium in TlCl[1] have now been augmented by preliminary determinations of the diffusion of chlorine. In the range 300–360°C the ratio of the chlorine diffusion to that calculated from the total conductivity by the Einstein relation is found to be 0.70 to 0.76. This ratio is appreciably larger than the 0.02 to 0.03 observed for thallium diffusion. Hence, it appears that Schottky defects are predominant, with chlorine vacancies considerably more mobile than thallium vacancies despite the smaller size of thallium ions. The expected value of this ratio, which should be equal to the Bardeen-Herring correlation factor, is only 0.655; however, for vacancies moving on a simple cubic lattice as in TlCl, and the difference is greater than the experimental error of 4%. Thus, additional diffusion mechanisms must be present to some extent. Several possible mechanisms will be discussed, and these results will be compared to those for CsBr and CsI, which have the same crystal structure and show the same general kind of behavior.[2]

[1] R. J. Friauf, Bull. Am. Phys. Soc. **3**, 127 (1958), and J. Phys. Chem. Solids (to be published).
[2] D. W. Lynch, Phys. Rev. **118**, 468 (1960).

IA9. Volume and Surface Conductivity of Borosilicate Glass. JULIUS J. MURAY, *University of California, Berkeley* (introduced by Leonard B. Loeb).—By using a variety of modern measuring techniques of great resolving times range, new data on normal bulk conductivity over a temperature range and surface conductivity produced when an electron beam strikes the surface of 7440 Pyrex were obtained. It is shown that the hitherto supposed fundamental exponential decline of bulk conduction current represents an instrumental RC time-conditioned phenomenon. The unexplained "anomalous" linear component of minutes duration represents current in which alkali ion carriers migrate to build up the anode and cathode potential falls characteristic of steady state conduction. Current is controlled by rate of recombination of alkali ions with electrons from the cathode in the cathode fall. Equations governing permit evaluation of activation and dissocation energies of the atoms. With known ion and electron mobilities recombination, diffusion coefficients, and cathode fall data were obtained. The spread of the electron beam projected onto the surface, by surface charge in less than 10^{-8} sec, is computed. Surface charge further spreads over the surface by self-repulsion in milliseconds. The spread is quickly arrested and surface charge is attenuated by neutralization and recombination through migration of alkali ions from the interior. The residual charge left in the interior by ion movement leaks to ground through the glass on time scales of tenths of a second.

TUESDAY MORNING AT 9:30

Terrace Room, Mark Thomas Inn

(L. E. KINSLER presiding)

Elastic Properties

J1. Pressure Dependence of Elastic Vibrations in Alkali Metals. J. C. ERDMANN, *Boeing Scientific Research Laboratories* (introduced by R. W. Moss).—According to the statistical theory the elastic constants of alkali metals can be expressed simply in terms of the lattice energy for zero pressure and the lattice parameter. The pressure dependence of the lattice parameter gives rise to a corresponding dependence of the elastic wave velocities and the polarization vectors, which has been calculated for sodium and potassium.

J2. Pressure Dependence of the Elastic Shear Constants of Li.* A. L. JAIN, *Case Institute of Technology.*—The elastic shear constants C_{44} and $C'=\frac{1}{2}(C_{11}-C_{12})$ of lithium have been measured as a function of pressure at room temperature. The measured values of the quantity, $-d\ln C/d\ln r$ are C_{44}, 4.1; C', 2.8. This inequality of the two pressure variations is contrary to the situation found in sodium,[1] where the two coefficients were equal. Theoretically, the two coefficients are expected to be the same, if only the electrostatic interaction between the electrons and the ions is responsible for the elastic stiffness of the metal. The different behavior in lithium can be understood in terms of the extra contribution to the shear constants arising due to the change in the Fermi energy of the electrons on shearing.

* Supported by the Office of Naval Research and the National Carbon Company.
[1] W. B. Daniels, Phys. Rev. **119**, 1246 (1960).

J3. Elastic Constants of Li-Mg Alloys.* J. TRIVISONNO AND CHARLES S. SMITH, *Case Institute of Technology.*—The single crystal elastic constants of dilute lithium-magnesium alloys were measured using the ultrasonic pulse-echo technique. In terms of $d\ln C/dx$, all fundamental elastic constants increase with composition by the following amounts: C_{44}, 1.22; C', 1.03; B_s, 1.2; per atom fraction. Small corrections for lattice parameter change upon alloying were made for C_{44} and C' by using the pressure derivatives of the elastic constants of pure lithium and the known variation of the lattice constant with composition. The remaining effect is ascribed to alloying alone. Both to understand the elastic shear constants of lithium and to comprehend their dependence on composition, one must include small negative stiffness contributions arising in the Fermi energy, in addition to the major and usual electrostatic stiffness. It is then possible to deduce the variation with composition of each contribution from the measured total variation for the two shear constants, with the result that $d\ln C_E/dx=1.24$ and $d\ln C_F/dx=1.76$. Both values are reasonable.

* Work was supported by the U. S. Atomic Energy Commission and the National Carbon Company.

J4. Closed-Shell Repulsive Potential for the Noble Metals. J. S. KOEHLER, *University of Illinois,** AND G. E. DUVALL, *Stanford Research Institute.*†—McQueen and Marsh use the Mie Gruneisen theory to correct their shock wave data to 0°K. The resulting pv curves are fit to $W(v)=A(v_0/v)+B(v_0/v)^{\frac{1}{2}}-C(v_0/v)^{\frac{1}{3}}+H\exp\alpha[1-(v/v_0)^{\frac{1}{3}}]$, where W is the energy per atom, v_0 the atomic volume at zero pressure, and v the atomic volume under pressure p. The fit used (1) $W(v_0)$, (2) $p(v_0)$ is zero, (3)(4)(5) three points along the pv curves (pressures up to 1.5 megabars). If we assume zero yield stress we find ($ABCH$ are, in 10^{-12} ergs per atom):

	A	B	C	H	α
Cu	+4.0000	−5.8504	+17.8438	+1.7440	10.06
Ag	−2.8256	+0.0613	+16.6623	+2.5017	10.00
Au	−15.8917	+8.5219	+18.3760	+5.0969	9.65

If the yield stress is 7 kbar independent of pressure:

	A	B	C	H	s
Cu	+3.1925	−1.5029	+20.9466	+1.3068	11.0
Ag	−4.3543	+7.2170	+21.6293	+1.8417	11.0
Au	+6.2612	−26.1767	−4.7221	+3.9887	9.6

* Research assisted by the U. S. Atomic Energy Commission.
† Research assisted by the Air Force Office of Scientific Research.

J5. Temperature Dependence of the Maximum Modulus of NaCl. JAMES P. CUSICK, *NASA, Lewis Research Center* (introduced by P. R. Behrendt).—The temperature dependence of the stress-strain curve for single crystals of sodium chloride has been measured by constant strain-rate compression test with $\dot{\epsilon} \sim 10^{-4}$. As previously reported,[1] no Hookian behavior was evident. The "maximum modulus" is defined as the maximum value of the slope of the measured stress-strain curve prior to gross plastic deformation. The variation of this parameter with temperature exhibits a tenfold decrease from the room temperature value in the temperature range −80° to −200°C. Likewise a twofold decrease is observed in the temperature range +50° to +150°C.

[1] Stearns, Pack and Lad, NASA TN-*D75* (October, 1959).

J6. Low-Temperature Thermal and Elastic Properties of Solid Argon. ROBERT M. WINTER, *Research Laboratories, United Aircraft Corporation.*—The Helmholtz free energy of a crystal at low temperatures separates into the static energy due to the average positions of the atoms in the lattice and the vibrational energy, the latter consisting of zero-point and thermal contributions. When the lattice is strained, all three depend on the strain parameters and hence contribute to the elastic constants. In the quasi-harmonic approximation the potential energy of the strained lattice is expanded to quadratic terms in the displacements of the atoms from their equilibrium positions in the real crystal. The thermal and elastic properties have been calculated using a Lennard-Jones 6–12 potential with force constants determined from crystal data. In the calculation of the temperature dependent contributions the condition has been imposed that the free energy be a minimum for the crystal in equilibrium at each temperature. The elastic constants at 0°K have been given in a previous paper[1] and the compressibility, thermal expansion, specific heat, C_{11}, C_{12}, and C_{44} are herein presented for the temperature range 0° to 10°K.

[1] R. M. Winter and A. A. Maradudin, Bull. Am. Phys. Soc. **4**, 226 (1959).

TUESDAY AFTERNOON AT 2:00

421 Spanagel Hall

(W. P. SLICHTER presiding)

High-Polymer Physics. II

Invited Papers

JA1. Some Aspects of Polymer Tacticity. F. GORNICK, *National Bureau of Standards.* (30 min.)
JA2. Magnetic Resonance in Silicone Polymers. J. G. POWLES, *Queen Mary College.* (30 min.)

Contributed Papers

JA3. High-Resolution Proton Magnetic Resonance of Polystyrene. PAUL H. LINDENMEYER AND WALLACE C. LAWRENCE, *Chemstrand Research Center, Inc.*—The high-resolution proton magnetic resonance of polystyrene solution has been measured by several authors.[1–3] In each case, it was found possible to resolve resonance peaks for the ortho and the meta-para aromatic protons. In addition, McCall and Bovey[3] detect a spin-spin splitting of these two peaks. The aliphatic proton resonance peak, according to Bovey,[1] is resolved only for very low molecular weight, whereas Kern and Pustinger[2] observe a partial splitting for isotactic polystyrene. We have measured the 60-Mc resonance spectra of polystyrene in a variety of solvents and find that it is possible to obtain a splitting of the aliphatic proton resonance peak for both the atactic and isotactic polymers. The extent of this splitting appears to be a function of the particular solvent used. These results are discussed in terms of the implications they have on the determination of the configuration of polymer chains and the conformation of these chains in various solutions.

[1] F. A. Bovey, G. V. D. Tiers, and G. Filipovich, J. Polymer Sci. **38**, 73 (1959).
[2] R. B. Kern and J. V. Pustinger, Nature **185**, 236 (1960).
[3] D. W. McCall and F. A. Bovey, J. Polymer Sci. **44**, 530 (1960).

JA4. Nuclear Magnetic Relaxation in Polymer Liquids and Solutions. DAVID W. MCCALL, DEAN C. DOUGLASS, AND ERNEST W. ANDERSON, *Bell Telephone Laboratories, Inc.*—Earlier studies of nuclear magnetic relaxation in molten polyethylene have been extended to include polydimethylsiloxane and polyisobutylene in the melt and in solution. The following factors are common to the behavior of these three polymers: (1) transverse relaxation, for polymers of sufficiently high molecular weight, can usually be closely approximated by two exponential decays (two T_2's); (2) longitudinal relaxation can always be described by a simple exponential law (one T_1); (3) T_2 and T_1 exhibit activation energies which are nearly equal but that for T_1 is always slightly smaller; (4) transverse relaxation appears to approach a simple exponential decay (one T_2) at sufficiently high temperature or sufficiently great dilution in a low molecular weight solvent; (5) T_1 is substantially longer than T_2 in all cases. The distributions of molecular weights affect the relaxation results, but experiments indicate that this is not the origin of the peculiar behavior. A theoretical model for calculating the distribution of molecular correlation times has been developed, but such a distribution, alone, does not appear to predict all the above-mentioned features. We cannot explain the effects in terms of an explicit theory, but we shall discuss the promise of models based upon molecular conformation and entanglement concepts.

JA5. Proton Magnetic Resonance of some Poly(Alpha Olefins).* A. E. WOODWARD A. ODAJIMA AND J. A. SAUER, *Pennsylvania State University.*—Proton magnetic resonance spectra of a series of polyolefins: polypropylene, poly(3, 3′, 3″ trideuteropropylene), PTDP, poly(butene-1), PB1, poly (pentene-1), PP1, poly(3 methyl butene-1), P3MB1, and

poly(4 methyl pentene-1), P4MP1, have been obtained from 77° to 300°K or higher. The line narrowing in the 77° to 150°K region reported previously for polypropylene is not exhibited by PTDP which is further evidence that this process is a consequence of methyl group rotation. Both P3MB1 and P4MP1 show distinct line narrowing and second moment changes in the 77° to 130°K region, this change being attributed to the onset of methyl group rotation. The second moment-temperature curves for PP1 and PB1 are similar to each other with no marked line-narrowing processes occurring until temperatures of 260° to 300°K are reached. However, by a comparison of experimental and calculated second moments it appears that considerable motion, presumably methyl rotation, is taking place in PB1 and PP1 at 77°K. All polymers studied show line narrowing and second-moment changes around room temperature which are believed to be due to reorientation motions associated with the glass transition. These NMR motional narrowing processes occur in the order PP1≤PB1 ≃PTDP <polypropylene <P4MP1 <P3MB1.

* Supported in part by U. S. Atomic Energy Commission contract.

JA6. Analysis of Orientation and Strength of Branched Polymer Model Solid.* T. S. Wu and C. C. Hsiao, *University of Minnesota.*—An analysis is made to determine the effect of molecular orientation on the breaking strength of a branched high polymer model solid. It is found that the relative variation of the strength of a model solid with side chains or branches as a result of either uniaxial or biaxial orientation is less than that without.[1-3] An attempt is also made to analyze the strength of a specific model which is thought to be approximately analogous to the molecular structure of polymethyl methacrylate. The theoretical result thus obtained agrees fairly well with some known experimental data.

* Supported in part by the U. S. Atomic Energy Commission.
[1] C. C. Hsiao, J. Appl. Phys. **30**, 1492 (1959).
[2] A. Robinson, J. E. Osborn and C. C. Hsiao, J. Appl. Phys. **31**, 1604 (1960).
[3] C. C. Hsiao, J. Polymer Sci. **44**, 71 (1960).

JA7. Effect of γ Irradiation on Strength of Oriented Polyethylene.* C. C. Hsiao and J. W. Yang, *University of Minnesota.*—Oriented samples of polyethylene irradiated by γ rays have been investigated at room temperature. On the basis of tensile studies both the ultimate strength and the modulus of elasticity are found to increase as the degree of orientation increases. But the ultimate strength decreases as the dose of γ irradiation increases while the modulus of elasticity increases. The combined effects seem to indicate that the γ irradiation essentially destroys the molecular orientation and thus reduces the ultimate strength for either uniaxially or biaxially oriented samples.

* Supported in part by the U. S. Atomic Energy Commission.

JA8. Statistics of Orientation Effects in Linear Polymer Molecules. Edmund A. DiMarzio, *American Viscose Corporation.*—This paper is concerned with the effects of orientation on the combinatorial term g for the number of ways to pack together N_x linear polymers (x-mers). Accordingly g is evaluated as a function of the number of molecules in each permitted direction for the case of straight rigid rods. The permitted directions can be continuous so that g is derived as a function of the continuous function $f(\Omega)$ which gives the density of rods lying in the solid angle $\Delta\Omega$, or the permitted directions can be discrete so that g is the number of ways to pack molecules onto a lattice. To illustrate the usefulness of the orientation-dependent combinatorial terms, liquid crystals are discussed. Another phase is found to exist in addition to the previously predicted nematic phase. This phase is tentatively identified with the cholesteric phase. A procedure is developed for the calculation of the orientation-dependent combinatorial term associated with the packing together of molecules of arbitrary shape. A very approximate application of this procedure results in an approximate expression for the combinatorial term which allows one to predict qualitatively the change in the entropy of packing as a function of stretch. It is found that the entropy of packing has the proper behavior to explain the initial deviation of the experimental stress-strain curve from the previous theoretical predictions.

Business Session of the Division of High-Polymer Physics

Tuesday Afternoon at 2:00

400 Spanagel Hall

(C. Shull presiding)

Mössbauer Effect

Invited Paper

K1. Some Applications of the Iron 57 Mössbauer Effect in Magnetism. G. K. Wertheim, *Bell Telephone Laboratories, Murray Hill.* (30 min.)

Contributed Papers

K2. Resonance Scattering of Linearly Polarized Gamma-Rays on Nuclei.* G. Felsner† and M. E. Rose, *Oak Ridge National Laboratory.*—The coherent resonance scattering of linearly polarized gamma rays on nuclei is calculated with angular correlation methods. Hyperfine splitting is assumed. The result is discussed for the Mössbauer nuclei Fe^{57} and Ni^{61} with a simple geometry (the magnetic field and the directions of the absorbed and the reemitted quantum are mutually perpendicular). The geometry optimizes the coherent contribution to the resonance scattering. The dependence of the scattering intensity on an external magnetic field implies, under favorable circumstances, a measurement of the magnetic moment of the excited state (independently of the ground state splitting) and also of the internal field acting on the nucleus.[1]

* Supported by U. S. Atomic Energy Commission and Deutsche Forschungsgemeinschaft.
† On leave from Physikalisches Institut der Universität Erlangen.
[1] Oak Ridge National Lab. Rept. ORNL-3042.

K3. Excitations of Phonons in Liquids and Crystals through Gamma-Ray Scattering. ROGER B. DEBAR, *Stanford University.*—Little[1] has recently proposed experiments to determine the phonon spectra of He II and other kinds of condensed matter, through direct measurement of the energy shift in gamma-ray scattering by means of the Mössbauer effect. Some of the results expected from such experiments are analyzed here, in analogy with Van Hove's[2] work on cold neutron scattering. The general results so obtained are then specialized to the case of a fluid, such as He II, in which quantum effects predominate, and lead to a well-defined phonon excitation spectrum for scattering. The simple formula for the energy-dependent scattering differential cross section is discussed in terms of familiar physical principles. An expression is obtained in similar fashion for the cross section for scattering from simple crystals, and the result for the special case of a cubic lattice of harmonically bound atoms is investigated in detail. Problems of background scattering in crystals are considered and compared with the absence of such scattering in the case of a quantized liquid.

[1] W. A. Little (private communication).
[2] L. Van Hove, Phys. Rev. 95, 249 (1954).

K4. Localized Lattice Vibrations and the Mössbauer Effect.* BERNARD MOZER AND GEORGE H. VINEYARD, *Brookhaven National Laboratory.*—Localized lattice vibrational modes associated with impurity atoms should be observable through a modification of the Mössbauer effect. If the impurity atom has a gamma emitting isomer of suitable lifetime, its gamma emission or absorption spectrum will be sharply modified by the localized lattice modes. A theoretical analysis has been made, and it shows that satellites appear about the Mössbauer peak at multiples of the localized mode frequency. The broadening of the localized mode caused by anharmonicities in the lattice has been estimated and found to be sufficiently small to permit observations. Under certain conditions the absorption at the localized mode frequency is a large fraction of the total absorption by the modes of the continuum so that the satellites should be distinguishable from background. Specific systems have been investigated theoretically. One can also demonstrate that an enhanced Mössbauer effect can be obtained by a suitable choice of host lattice.

* Work supported by the U. S. Atomic Energy Commission.

K5. Mössbauer Effect and Directional Dependence of Threshold Displacement Energy. U. GONSER, *Atomics International* (introduced by A. Sosin).—In some cases, the foregoing β decay of isotopes available for Mössbauer resonance absorption is energetic enough that the isotope can be displaced in a lattice by the recoil. The β radiation indicates the direction of the recoil and can also be used as a signal for the following recoil-free γ decay. Ga^{73}, with a 1.4-Mev β decay, is suitable for studying this effect. The half-life of the resulting Ge^{73} is 4.6×10^{-9} sec. The intensity of the recoil-free 13.5-kev radiation depends strongly on the Debye temperature. The oscillator spectrum around an atom which is displaced to an interstitial site is changed, so that the intensity of the Mössbauer line gives an indication if the atom in question is displaced or not. Replacement collisions are unlikely in materials with the diamond structure. If a β counter is moved with respect to a single crystal of germanium doped with Ga^{73}, a β-γ coincidence device would count the intensity of the recoil-free γ line of all recoils within a specific solid angle.

K6. Mössbauer Effect in γ-Fe_2O_3.* W. H. KELLY, M. HASS,† W. N. SCHREINER,‡ AND G. B. BEARD,§ *Michigan State University.*—The Mössbauer effect and hyperfine spectrum of Fe^{57} in γ-Fe_2O_3 has been observed. The spectrum is very similar to that of iron metal, giving equally spaced Zeeman levels for the first excited state of Fe^{57} in the crystal. The spectrum can be interpreted in terms of a magnetic field at the nucleus of Fe^{57} of $(5.2\pm0.3)\times10^5$ oe. No difference in the field can be observed between the Fe^{3+} ions in the octahedral and tetrahedral sites. Since the Fe^{3+} ions are in S states and located in a cubic field in an insulator, the hyperfine spectrum can be attributed largely to the Fermi contact interaction with the contributions from other effects being small.

* Supported in part by the U. S. Air Force Office of Scientific Research.
† Permanent address: U. S. Naval Research Laboratory, Washington, D. C.
‡ N.S.F. Undergraduate Research Participant.
§ Present address: Wayne State University, Detroit, Michigan.

K7. Isomeric Chemical Shifts in Odd-Proton Nuclei.* D. A. SHIRLEY, *Lawrence Radiation Laboratory and Department of Chemistry, Berkeley.*—In recent studies of the Mössbauer effect in Au^{197}, chemical shifts were observed which are an order of magnitude larger than any previously reported.[1] We attribute this greater shift to the fact that gold is the only element of odd atomic number in which the effect has been studied in several chemical environments. The shift may then be understood as arising from different potential energies of the odd proton in the two isomeric states due to interaction with the Coulomb field created by valence electrons within the nucleus. This field is dependent on the environment of the gold atom. Thus this shift may be used to study chemical properties or, alternatively, the radial distribution of the odd proton inside the nucleus. The shift may also be used to test recent ideas concerning internal fields in ferromagnetic materials. By using first-order perturbation theory and the usual Dirac (finite-nucleus) wave functions for the $6s$ electron of gold, we have calculated shifts for several nuclear models.

* Work done under the auspices of the U. S. Atomic Energy Commission.
[1] P. Axel, M. Kaplan, and D. A. Shirley, Lawrence Radiation Laboratory (unpublished work).

K8. Systematics of the Fe^{57} Isomer Shift. G. K. WERTHEIM, L. R. WALKER, AND V. JACCARINO, *Bell Telephone Laboratories, Inc.*—Study of the displacement of the centroid of the resonant absorption energy in the Fe^{57} Mössbauer effect in divalent and trivalent compounds and in d-group metals has shown a systematic behavior related to the electronic configuration of the iron. All measurements were made relative to type 310 stainless steel with source and absorber at room temperature. Effects of the second-order Doppler shift and the zero-point energy shift tend to cancel when the difference in shifts of similar compounds is considered. The values obtained for the shift are: Divalent compounds: FeF_2, 0.140; FeF_3, 0.139; $FeSO_4\cdot7H_2O$, 0.140; $FeCl_2\cdot4H_2O$, 0.130; FeS, 0.11. Trivalent compounds: $Fe_2(SO_4)_3\cdot6H_2O$, 0.052; Fe_2O_3, 0.047; YIG octahedral site, 0.057; YIG tetrahedral site, 0.026. Metals: Fe^{57} in Fe, 0.015; Co, 0.012; Ni, 0.015; Mn, −0.008; Cr, −0.005; Mo, −0.001. The measurements show a characteristic shift of 0.14 and 0.05 cm/sec for the most ionic divalent and trivalent compounds and a very small shift for the metals. On using an estimate for the total s-electron density for the ionic d^5 and d^6 configurations of iron (see following abstract) and the difference in the shifts in the di- and tri-valent compounds, the difference in the radii of the isomeric and ground states of Fe^{57} has been obtained; $R_{ia}-R_{gr}/R = -1.8\times10^{-3}$, where it is assumed $R=1.20\ A^{\frac{1}{3}}\times10^{-13}$ cm.

K9. Interpretation of the Fe^{57} Isomer Shift. L. R. WALKER, G. K. WERTHEIM, AND V. JACCARINO, *Bell Telephone Laboratories, Inc.*—The isomer shift in the Mössbauer effect is proportional to the difference in total s-electron density at the Fe nucleus in emitter and absorber. The consequences of one tentative calibration of the shift in terms of actual s-electron density have been explored. This calibration identifies the difference in isomer shifts for the most ionic of the divalent and trivalent Fe compounds with the difference between the total s-electron density for Fe $3d^6$ and $3d^5$ configurations as

calculated by Watson[1] with the restricted Hartree-Fock method. The difference in charge radii of the two states of Fe^{57} may now be estimated. The shifts in the less ionic compounds and in *d*-group metals are associated with *3d* configurations to which some fraction of a *4s* electron has been added. The *4s*-electron density at the nucleus may be obtained with sufficient accuracy from the Fermi-Segrè-Goudsmit formula. A satisfactory interpretation of the metal data, consistent with the requirement that eight electrons are associated with an Fe ion in iron, is that the Fe ion is in all cases very close to a $3d^7$ *4s* configuration.

[1] R. E. Watson, Solid-State and Molecular Theory Group, M.I.T., Tech. Rept. No. 12 (June 15, 1959).

K10. Nuclear Polarization Study by Means of the Mössbauer Effect. J. G. DASH, *University of Washington*, AND R. D. TAYLOR, D. E. NAGLE, P. P. CRAIG, AND W. M. VISSCHER, *Los Alamos Scientific Laboratory*.—A study has been made of the effect of low temperatures on the resonant emission and absorption of 14.4-kev Mössbauer radiation from Fe^{57} in Fe metal. Analysis of intensity changes in the hyperfine spectrum is made in terms of the Zeeman level splittings of the ground states of Fe^{57} absorbing nuclei and of the ground states of Co^{57} parent nuclei. The theory for the temperature dependence is developed in terms of the properties of the Co^{57} decay and of the subsequent gamma transitions. Experiments were carried out with a source of Co^{57} nuclei in Fe metal at temperatures between 4.5° and 0.85°K. The experimental results, analyzed in terms of the theory, yield a value of the hyperfine magnetic field of 300±20 kgauss at the Co^{57} nuclei. Comparison of the result with other pertinent experimental values indicates that depolarization of the nuclei by the *K*-capture decay of Co^{57} is not evident in the present material.

TUESDAY AFTERNOON AT 2:00

Ballroom, Herrman Hall

(P. KAUS presiding)

Electron Transport in Semiconductors, Thermoelectricity

KA1. Impurity Conduction in Strained *n*-type Germanium. H. FRITZSCHE, *University of Chicago*.—Impurity conduction of germanium doped with antimony or with arsenic has been measured as a function of uniaxial compression along [111]. Using Sb as donors the resistivity measured along [111] rises rapidly with increasing compression by more than a factor of 10^7 at low temperatures. Saturation is reached when the strain-induced shift of the conduction band valleys becomes larger than the valley-orbit splitting. The resistivity measured perpendicular to the stress direction remains almost unchanged. The resistivity anisotropies and resistivity changes are several orders of magnitude smaller in arsenic-doped germanium at comparable stresses. This is due to the larger valley-orbit splitting of As donors. These effects can be explained in terms of the strain-induced change of the impurity ground state wave function and of the low-temperature activation energy of impurity conduction.

KA2. Transport in *n*-Type Germanium Subject to Large Strains. JOHN J. HALL, *Columbia University and IBM Watson Laboratory*, AND S. H. KOENIG, *IBM Watson Laboratory*.—Samples of high purity *n*-type germanium have been subjected to large (~½%) uniaxial compressive strains in the ⟨111⟩ direction from 4.2°K to 300°K and their electrical conductivity measured. The strain obtained was sufficient to lower the energy of the ⟨111⟩ band minimum relative to the remaining three so that essentially all of the free carriers were in the ⟨111⟩ valley over much of this temperature range, as evidenced by the saturation of the piezoresistance. The conductivity under saturation is observed to vary approximately at $T^{-1.45}$ from the exhaustion region up to 150°K, vs a $T^{-1.60}$ dependence with no strain applied. The stronger temperature dependence of the zero strain conductivity may be ascribed to intervalley scattering processes, absent under saturation strain conditions. The deformation potential for shear strain was found to be 19.8±0.2 ev, and essentially temperature independent over the entire range of measurement, in contrast with previously reported values in the temperature range above 20°K.[1]

[1] See, for example, Gabriel Weinreich, T. M. Sanders, Jr., and Harry G. White, Phys. Rev. 114, 33 (1959).

KA3. Room-Temperature Piezoresistance and Elastoresistance in *p*-Type PbTe. J. R. BURKE, JR., B. B. HOUSTON, JR., AND R. S. ALLGAIER, *United States Naval Ordnance Laboratory*.—From longitudinal, transverse, and hydrostatic piezoresistance measurements on pulled lead telluride single crystals having about 3×10^{18} holes/cm³ we find that π_{11}, π_{12}, and π_{44} equal 24, 15, and 215×10^{-12} cm²/d. These results, which we believe are accurate to about 10%, differ considerably from earlier data.[1] From elastic stiffness values[2] $\frac{1}{2}(c_{11}+2c_{12})$, $\frac{1}{2}(c_{11}-c_{12})$, and $c_{44}=4.16$, 4.90, and 1.31×10^{11} d/cm² and from our piezoresistance data we obtain the elastoresistance values $\frac{1}{2}(m_{11}+2m_{12})=23$, $\frac{1}{2}(m_{11}-m_{12})=4.4$, and $m_{44}=28$, revealing that there is much less shear anisotropy in the elastoresistance than in the piezoresistance. The elastoresistance data show nevertheless that $m_{44}\gg\frac{1}{2}(m_{11}-m_{12})$ as expected for a ⟨111⟩ multivalley model, and this is consistent with the observed symmetry of the weak-field magnetoresistance.[3] However, the pressure coefficient[4] $\frac{1}{2}(m_{11}+2m_{12})$ is very large for an extrinsic sample and indicates the presence of a second valence band, as does also the Hall coefficient behavior as a function of temperature.[4]

[1] L. E. Hollander and T. J. Diesel, J. Appl. Phys. 31, 692 (1960).
[2] R. E. Strakna and A. E. Clark (private communication).
[3] R. S. Allgaier, Phys. Rev. 119, 554 (1960).
[4] R. S. Allgaier, Czechoslov. J. Phys. (to be published).

KA4. Transport Properties of the Bi_2Te_3-Sb_2Te_3 Pseudo-Binary Alloy System in the Temperature Range 80°K–400°K. L. R. TESTARDI, J. N. BIERLY, JR., AND F. J. DONAHOE, *The Franklin Institute Laboratories*.—The Seebeck and Hall coefficients and the thermal and electrical conductivities of a number of *p*-type, single crystal alloys from the $(B, Sb)_2Te_3$ pseudo-binary system have been measured in the temperature range 80—400°K. Anomalies have been found in the hole mobility and density of states effective mass at compositions $Bi_{1.33}Sb_{0.67}Te_3$; $Bi_{0.67}Sb_{1.33}Te_3$ and $Bi_{0.48}Sb_{1.60}Te_3$. The room temperature lattice thermal conductivity of the alloy series has a minimum value of 0.010 w/cm deg at $BiSbTe_3$. The temperature dependence of the lattice thermal conductivity shows the effect of phonon scattering from lattice disorder. Some evidence of acoustical scattering of the holes may be

obtained from the temperature dependence of the Hall mobility once corrections have been made for the effects of degeneracy and the temperature dependence of the density of states effective mass. The room temperature variation of Seebeck coefficient, electrical conductivity, and thermoelectric figure of merit with carrier concentration were computed using exact statistics. Good agreement with experimental data was found except for specimens with very large carrier concentration.

KA5. Thermoelectric Power of Bismuth-Antimony Alloys at Low Temperatures. G. E. SMITH AND R. WOLFE, *Bell Telephone Laboratories, Inc.*—The thermoelectric power, resistivity, and thermoelectric figure of merit have been measured in the temperature range between 300°K and 20°K for alloys in the range of 5% to 40% antimony in bismuth. Galvanomagnetic measurements by Jain[1] have shown that these alloys exhibit semiconducting characteristics which have a maximum effective gap of 0.014 ev for concentrations of about 12% antimony in bismuth. For the 12% alloy, the thermoelectric power is *n*-type and shows a gradual rise from 125 μv/°K at 300°K to 150 μv/°K at 80°K and then falls off rapidly. The figure of merit Z shows the same behavior and has a maximum of $Z=5\times10^{-4}$ at 80°K. In a 12% alloy doped with 0.01% lead, the thermoelectric power changes from *n*-type at high temperatures to *p*-type at temperatures below 40°K. The use of this material in a low-temperature thermoelectric refrigeration seems feasible.

[1] A. L. Jain, Phys. Rev. 114, 1518 (1959).

KA6. Electron-Electron Scattering and Transport Phenomena in Nonpolar Semiconductors. J. APPEL, *General Atomic.*—The effect of electron-electron (e-e) scattering processes on the transport phenomena in nonpolar isotropic solids is treated in the framework of the variational method. By considering the conduction electrons as a gas of noninteracting free quasiparticles, e-e scattering is taken into account as a small perturbation, as is electron-phonon scattering. The pair interaction between two electrons is described by a shield Coulomb potential. A general qualitative result is that e-e scattering causes the electrical conductivity to be reduced *less* than the electronic heat conductivity; the difference occurs because the former is a zero-order transport phenomenon while the latter is a first-order one. The electrical conductivity, the heat conductivity, and the Wiedman-Franz ratio will be reduced by an amount determined by the energy dependence of that perturbation of the electron distribution which is induced by primary scattering sources such as electron-phonon scattering or electron-impurity scattering. Quantitative results are obtained for nondegenerate semiconductors. With electron-phonon and electron-ion scattering assumed in turn as the primary scattering mechanism, the influence of e-e scattering on the three transport coefficients is calculated as a function of temperature. The applicability of the results obtained for isotropic semiconductors to an important class of anisotropic semiconductors is shown. The effect of e-e scattering on the transport phenomena in metals is briefly considered.

KA7. Magnetic Field Dependence of the Low Temperature Thermoelectric Power in *n*-Type Silicon. R. S. KROGSTAD AND R. W. MOSS, *Boeing Scientific Research Laboratories.*—Measurements of the magnetic field dependence of the thermoelectric power in high-purity phosphorous-doped silicon will be reported. At temperatures above about 35°K, and with fields up to 24 kgauss, the thermoelectric power behaves in a normal manner with magnetic field. However, below this temperature the thermoelectric power has been observed to rise to a maximum, then decrease with increasing field. Indeed, for sufficiently low temperatures and high-field strengths, the differential thermoelectric power becomes negative. These results will be discussed in the light of a recent study by Appel,[1] in which the deviation of both the electrons and phonons from equilibrium is taken into account.

[1] J. Apfel, Z. Naturforsch. 13a, 386 (1958); 14a, 838 (1959).

KA8. Electric Dipole Scattering in Nonpolar Semiconductors. W. B. TEUTSCH AND J. APPEL, *General Atomic.*—Low-temperature experiments[1] on the electronic mobility in germanium containing Ga^+-Li^- ion pairs indicate that Coulomb scattering by the individual ions is not the dominant scattering mechanism and suggest that scattering by the electric dipole moments of the associated ion pairs may be important. The differential cross section for the scattering of a charged particle by an electric dipole is calculated in the Born approximation. This cross section is used to obtain relaxation time and mobility of electronic charge carriers. Two special cases are considered: (1) all dipole moments oriented parallel, (2) random orientation of the dipoles. For a nondegenerate electron gas, the relaxation time is found to be proportional to $E^{\frac{1}{2}}$ and the mobility, to $T^{\frac{3}{2}}$.

[1] Reiss, Fuller, and Morin, Bell System Tech. J. 35, 535 (1956).

KA9. Low-Field Breakdown in *p*-Type Germanium in Inhomogeneous Electric Fields. H. SHENKER, *U. S. Naval Research Laboratory.*—The electrical noise and conductivity of variously shaped samples of *p*-type germanium were studied in the liquid helium temperature range as a function of applied voltage in order to obtain a measure of the noise characteristics of germanium in the "broken-down" condition without disturbing effects from the electrodes. It was found that noise maxima were generally associated with increases in the slope of the $\ln(d\sigma/dV)$ vs V curve. It was not uncommon to obtain noise powers which were equivalent to diode currents as high as 10^4 times the sample current. In many samples there were voltage ranges in which the noise appeared as irregularly spaced sharp spikes. The frequency dependence of the noise varied with the applied voltage for a given sample; in one case noise maxima were observed in the range 1 to 4 mc with considerable noise still remaining at 11 mc. These observations indicate that part of the current flow occurs in "bunches" and are not inconsistent with the breakdown occurring in thin filaments as suggested by McWhorter. The conductivity of asymmetrically shaped samples depended upon the polarity of the impressed voltage for voltages high enough for the conductivity to be nonohmic. In all cases the conductivity was greatest when the current carriers drifted in the direction of decreasing magnitude of electric field.

KA10. Energy and Momentum Relaxation Processes of Electrons in *n*-Type Germanium. THOMAS N. MORGAN, *IBM Research Laboratory, Yorktown Heights.*—We have measured dc resistivity and its dependence on the electric field with 3 cm microwaves in *n*-type Germanium samples having between 2×10^{13} and 3×10^{13} ions per cc. The variation of resistivity with temperature and the resistivity changes produced by weak microwave fields are sensitive to ion concentration, the former approaching $T^{1.75}$ dependence for the purer samples. Both agree with a theory based on temperature independent effective masses, acoustical phonon scattering, Brooks-Herring ion scattering, and optical phonon scattering with a coefficient of 0.55 times acoustical. The variation of this resistivity change with the microwave frequency used, interpreted in terms of effective energy relaxation times, are in reasonable agreement with theoretically predicted values between 77° and 300°K.

KA11. Warm Electrons Measurements in *n*-Type Germanium. S. BERMON* AND D. MEYERHOFER, *RCA Laboratories, Princeton, N. J.*—Direct-current measurements have

been made of the change in mobility at small electric fields in *n*-type germanium to further check the validity of a new theory.[1] Previous data[2] have been extended to room temperature with samples containing 7×10^{13} to 3×10^{17} cm^{-3} donors. The results of the purer crystals with phonon dominated scattering agree quantitatively with previous dc and microwave measurements. The mobility decreases with electric field by an amount which agrees qualitatively with the theory which takes account of accoustical mode and ionized impurity scattering and includes sufficient optical mode scattering to explain the low-field mobility behavior. The more heavily doped crystals in which impurity scattering is dominant do not behave as the theory predicts. At 77°K they do show a positive coefficient of mobility, but at higher temperatures the values are negative and proportional to those of the pure crystals. The change over always occurs between 77° and 100°K.

* Now at the Physics Department, University of Illinois.
[1] I. Adawi, Phys. Rev. 120, 118 (1960).
[2] T. B. Gunn, J. Phys. Chem. Solids 8, 239 (1959).

KA12. Carrier Transport and Scattering in $AgSbTe_2$. A. AMITH, *RCA Laboratories, Princeton.*—Measurements were carried out in the temperature range 77°–300°K on *p*-type $AgSbTe_2$ (with about 2% of Ag_2Te as a second phase). The quantities measured included conductivity, Seebeck coefficient, Hall effect and magnetoresistance, as well as longitudinal and transverse Nernst coefficients. The dominant type of scattering consistent with the various measurements over this temperature range is ionized impurity scattering. The Fermi level is 2.7 kT units inside the valence band at room temperature and 9 units inside the band at 77°K, so that Boltzmann statistics are inapplicable. The Hall coefficient rises by 30% from 77°K to 300°K. The carrier density is 9×10^{18} cm^{-3} and is constant over the whole range. The hole effective mass is 0.23 m. The Hall mobility rises from 75 to 120, and the conductivity mobility rises from 75 to 92 cm^2/v sec over this temperature range. The density of singly ionized impurities deduced is about thrice that of holes. The Nernst coefficients are consistent with the same scattering mechanism. The angular dependence of the magnetoresistance indicates that the band is not spherical, and that the anisotropy factor K is less that unity. The Hall coefficient exhibits strong dependence upon the magnetic field: it decreases as H increases.

KA13. Dependence of Hot Carrier Ionization of Ga and Cu Impurities in Ge on Carrier Temperature. DALE M. BROWN, *Purdue University,** AND RALPH BRAY, *Purdue University* and General Atomic.*—Hot carrier mobility and ionization studies were made in Ge in the 20°K range. The efficiency of ionization of Ga (E_i=0.01 ev) and Cu (E_i=0.043 ev) impurities was compared. Copper was diffused into the gallium doped samples with only slight effects on the mobility and gallium ionization characteristics. The carrier temperatures were deduced from the measured mobility of the hot carriers, which was analyzed[1] in terms of scattering by acoustical and optical phonons, and ionized impurities. For the gallium impurities 100% ionization was readily obtained. Most of the ionization occurs below 30 v/cm, at *carrier temperatures close to the lattice temperatures* at which an equivalent degree of ionization is obtained at low fields. Ionization of the copper was observable only above about 1000 v/cm at estimated temperatures much *higher* than the lattice temperatures required to give equivalent ionization. The relative inefficiency of the hot carrier ionization of the copper may be due to competition for the high energy carriers from optical mode excitation (0.037 ev) as suggested by Lampert[2] et al.

* Supported by Signal Corps contract.
[1] Ralph Bray and Dale M. Brown, Bull. Am. Phys. Soc. 5, 194 (1960).
[2] M. A. Lampert, F. Herman, and M. C. Steele, Phys. Rev. Letters, 3, 394 (1959).

KA14. Generation-Recombination Noise in Gold-Doped Germanium. LEO J. NEURINGER AND WILLIAM BERNARD, *Raytheon Research Division.*—A preliminary estimate of the capture cross-sections for free holes by the 0.041 ev donor level and the 0.145 ev acceptor level in *p*-type gold-doped germanium has been obtained from measurements of the generation-recombination noise spectrum in the range 10^0–10^7 cps. At 78°K the Fermi level of the sample studied was locked midway between the two gold levels, such that the noise spectrum exhibited the relaxation times characteristic of the two levels. A standard experimental technique was employed in which the sample noise is calibrated using a noise diode. A two impurity level model appropriate to the gold-doped germanium system was employed to predict the observed generation-recombination noise in terms of the capture cross sections. Reasonable agreement was obtained between theory and experiment, both with respect to the observed lifetimes and the magnitudes of the two noise contributions. The values of the total cross-sections were found to be $\sigma_A\sim10^{-12}$ cm^2, $\sigma_D\sim10^{-18}$ cm^2, in qualitative agreement with other independent measurements.

TUESDAY AFTERNOON AT 2:00

Terrace Room, Mark Thomas Inn

(P. P. EWALD presiding)

Insulators I

Invited Paper

L1. Ferroelectricity in KH_2PO_4. E. UEHLING, *University of Washington.* (30 min.)

Contributed Papers

L2. Absorption of Sound in Insulators. TRUMAN O. WOODRUFF AND HENRY EHRENREICH, *General Electric Research Laboratory.*—The theory of sound attenuation in structurally perfect dielectric crystals has been extended and applied to recent experiments by Bömmel and Dransfeld and by Jacobsen on the absorption of acoustic waves in crystalline quartz at frequencies from 10^9 cps to 2.4×10^{10} cps. The sound wave was assumed to vary the frequencies of the thermal phonons adiabatically. The complete Boltzmann equation was used to determine the response of the thermal phonon distribution to this disturbance, and the rate of energy transfer from the thermal phonons to the temperature bath was computed. In

the steady state, energy is supplied by the driving sound wave to the thermal phonons at the same rate, which gives the attenuation. Relaxation times were assumed for N and U processes. Since the effect of the sound wave on a thermal phonon depends on the relative polarization and wave-number vectors, the phonon distribution in a small spatial region tends to relax to a new temperature T^* which is determined by requiring local conservation of the total energy to first order. The present treatment leads to semiquantitative understanding of the rapid decrease in attenuation with decreasing temperature in the range in which the sound-wave period becomes comparable to the average thermal-phonon relaxation time.

L3. Electrolysis of Quartz; Effect upon Acoustic Behavior.* D. B. FRASER AND J. C. KING, *Bell Telephone Laboratories, Inc.*—The optical- and acoustic-absorption spectrum of quartz can be altered by subjecting the material to an axial electric field of 1 kv/cm at 500°C.[1] It has been observed[2] that at room temperature the acoustic absorption of some synthetic quartz, hydrothermally grown on a Z-cut seed plate, is reduced by as much as an order of magnitude by the electrolysis treatment. Recent studies suggest that this effect derives from an electrolysis-induced removal of a broad relaxation absorption centered about 130°C, for a frequency of 5 mc. Measurements of the absorption in quartz have been extended to near the α-β inversion point. At 200°C the absorption in natural quartz at 1 mc rises from a value of the order of 10^{-6} to a peak at 500°C of 10^{-3}, after which it drops to lower values. From the slope of Q^{-1} vs $1/T$ in the range of 200°C to 400°C, the calculated activation energy for the process is approximately 0.65 ev. Possible lattice defects responsible for the 130°C mechanical relaxation mechanism and the high temperature absorption will be discussed.

* Supported in part by a Signal Corps contract.
[1] J. C. King, D. L. Wood, and D. M. Dodd, Phys. Rev. Letters 4, 518 (1960).
[2] J. C. King *Proceedings 13th Annual Frequency Control*, Symposium (Asbury Park, New Jersey, 1959), p. 1.

L4. Effect of X Irradiation on Audiofrequency and Ultrasonic Dispersion in Synthetic Quartz Crystals. J. C. KING, *Bell Telephone Laboratories, Inc.*, AND E. R. FITZGERALD, *The Pennsylvania State University*.—Measurements of the acoustic absorption at 5 Mc before and after x irradiation of synthetic quartz crystals have shown that profound changes occur as a result of x irradiation and that the material can be restored to its initial acoustic state by annealing at 300°C. The complex shear compliance spectrum in the 50–5000 cps range also is drastically affected by x irradiation, but restored to its original condition by annealing. For example, a group of crystals, obtained from growth on a seed plate (oriented parallel with a z-minor rhombohedron), exhibited a resonance dispersion near 1500 cps which shifted to 1300 cps and tripled in magnitude as a result of x irradiation. A short anneal at 300°C restored the original small resonance near 1500 cps. These and similar results on other synthetic crystals indicate that: (1) the observed audiofrequency mechanical resonance dispersions reflect the defect-modified structure of the quartz; (2) x irradiation changes the defect structure; and (3) annealing restores the original defect conditions present before x irradiation. Comparison with the relaxation dispersion behavior at 5 Mc suggests that whereas ultrasonic measurements involves the interaction of the sound field with individual defects, the mechanical resonance dispersions at audiofrequencies result from the collective actions of defects (as they affect dislocation motion or slip), as proposed by Fitzgerald.

L5. On Material Resonances in Stressed Solids.[1] S. R. BODNER, *Brown University* (introduced by Rohn Truell).—Experimental observations of audio-frequency resonances in stressed crystalline solids are discussed in relation to the predictions of macroscopic stress strain laws that incorporate the resonances. A theory based upon dislocation behavior which gives a qualitative explanation of the resonances is outlined. The possibility of material strength prediction from the experimental complex modulus values is discussed.

[1] Sponsored by Office of Naval Research contract with Brown University.

L6. A Mechanism for the Large Piezoresistive Effects in Oxygen-Deficient $BaTiO_3$ Ceramic. BRENTON L. MATTES AND LEWIS E. HOLLANDER, *Lockheed Aircraft Corporation*.—A maximum in the hydrostatic and longitudinal piezoresistive coefficients was observed at the tetragonal-to-orthorhombic—phase transition. In the cubic phase (above 120°C), the coefficients were extremely small, but at the cubic-to-tetragonal—phase transition the coefficients abruptly increased. In the tetragonal phase (between −11°C and 120°C), the coefficients continued to increase to a maximum at the tetragonal-to-orthorhombic transition (−11°C). In the orthorhombic phase (between −11°C and ∼−80°C) the coefficients gradually decreased, becoming extremely small in the rhombohedral phase. Oxygen-deficient $BaTiO_3$ ceramics with 3% $PbTiO_3$ additive were reduced in a hydrogen atmosphere to a room-temperature resistivity of 1 to 10 Ω cm. Measurements of the resistivity and the longitudinal (π_l) and the hydrostatic (π_H) piezoresistive coefficients were made over the temperature range from −83°C to 140°C. At 25°C values for these coefficients are $\pi_l = 170\times10^{-12}$ cm²/d, and $\pi_H = 105\times10^{-12}$ cm²/d; while at −11°C (tetragonal-to-orthorhombic transition) these values rose to $\pi_l = 525\times10^{-12}$ cm²/d, and $\pi_H = 340\times10^{-12}$ cm²/d. The π_H has a nonlinear pressure dependence, decreasing with an increase in pressure above 2.7×10^8 d/cm². These results suggest a "secondary" piezoresistive mechanism arising from the strain-induced crystal structural changes. This mechanism is predominant at the tetragonal-to-orthorhombic —phase transition.

L7. Thermodynamic Transitions in Ferroelectric Colemanite. H. H. WIEDER AND A. R. CLAWSON, *U. S. Naval Ordnance Laboratory*.—Two successive second-order transitions were detected in single crystals of colemanite by means of dielectric and pyroelectric measurements. The first, at −12°C, is a transition from the paraelectric to the ferroelectric state. The second, at −38°C, causes a discontinuous change in polarization, the ferroelectric state being retained below this transition. Debye-Sherrer powder patterns obtained over a range of temperatures between +25°C and −70°C suggest an attendant crystallographic phase transition at −38°C only. Other dielectric, pyroelectric, and ferroelectric properties are interpreted in terms of external and crystalline biasing fields.

L8. Microwave Properties of the Ferroelectric Triglycine Sulfate.* RAY H. WHITE AND M. TINKHAM, *University of California, Berkeley*.—The dielectric constant of triglycine sulfate has been determined from transmission measurements at 4 mm. The complex dielectric constant has been found as a function of temperature in the region from room temperature to 90°C. This temperature region includes the Curie temperature, 49°C. Both the real and imaginary parts of the dielectric constant show a maximum as a function of temperature at the Curie temperature and a temperature dependent relaxation from the dc values, as has previously been found.[1]

* Supported in part by the Office of Naval Research, the National Science Foundation, and the Alfred P. Sloan Foundation.
[1] A. Lurio and E. Stern, J. Appl. Phys. 31, 1125 (1960); E. Nakamura and J. Furuichi, J. Phys. Soc. Japan 15, 2101 (1960).

L9. Systematics of the Piezoelectric Effect in II-VI Crystals.* HANS JAFFE, DON BERLINCOURT, AND LEBO SHIOZAWA, *Clevite Corporation*.—Measurement of the piezoelectric constants of hexagonal cadmium selenide and cubic zinc telluride,

together with published data on hexagonal cadmium sulfide,[1] hexagonal zinc oxide,[2] and cubic zinc sulfide,[3] shows the piezoelectric constants to increase with increasing atomic number of the cation and decreasing atomic number of the anion. The unit for d_{ik} is 10^{-12} coul/newton; for the cubic

	d_{33}	d_{31}	d_{15}	electrons
ZnTe	0.94	$-\frac{1}{2}d_{33}$	$-d_{33}$	0.05
ZnS	1.86	$-\frac{1}{2}d_{33}$	$-d_{33}$	0.20
ZnO	12.0	−4.7	∼−12	∼0.82
CdSe	7.84	−3.92	−10.51	0.51
CdS	10.32	−5.18	−13.98	0.64

crystals these constants are given in a rotated coordinate system with Z parallel to [111]. The last column gives the effective charge per atom calculated from the piezoelectric and elastic constants (not shown) under the assumption of constant nearest neighbor distances.

* Supported by Sandia Corporation and Wright Air Development Division.

[1] Jaffe, Berlincourt, Krueger, and Shiozawa, *Proceedings of the 14th Annual Symposium on Frequency Control* (Fort Monmouth, New Jersey, 1960), p. 19.

[2] A. R. Hutson, Phys. Rev. Letters **4**, 505 (1960).

[3] W. G. Cady, *Piezoelectricity* (McGraw-Hill Book Company, Inc., New York, 1946), p. 229.

L10. Piezoelectric Properties of Lithium Trihydrogen Selenite.* DON BERLINCOURT AND W. R. COOK, JR., *Clevite Corporation.*—Lithium trihydrogen selenite [$LiH_3(SeO_3)_2$] is ferroelectric[1] of symmetry class m, in which the only symmetry element is a plane which must contain the ferroelectric direction. A complete set of piezoelectric and dielectric constants (the first such set for a class-m crystal) was determined. Choosing Y as the normal to the symmetry plane and the ferroelectric direction as Z, this set is: $d_{11}=+23.2$, $d_{12}=-22.3$, $d_{13}=-12.1$, $d_{15}=-46.6$, $d_{24}=-12.8$, $d_{26}=-14.6$, $d_{31}=-18.4$, $d_{32}=+5.5$, $d_{33}=+19.9$, $d_{35}=+53.2$ (10^{-12} coul/newton), $\epsilon_{11}^T/\epsilon_0=29.6$, $\epsilon_{13}^T/\epsilon_0=-16.5$, $\epsilon_{22}^T/\epsilon_0=12.9$, $\epsilon_{33}^T/\epsilon_0=29.4$. The principal axes for the dielectric tensor are Y, 45° between $+X$ and $+Z$ in XZ plane, and 45° between $+Z$ and $-X$; the corresponding dielectric constants are 12.9, 13, and 46. The maximum value for d_{31}' is 46×10^{-12} c/n in a direction +120° from $+Z$ in the XZ plane. The maximum value for the hydrostatic d constant occurs at the same angle, and its value is -13×10^{-12} c/n. It is interesting that the maximum piezoelectric and dielectric constants occur far from the ferroelectric axis.

* Reserch sponsored by Sandia Corporation.

[1] R. Pepinsky and K. Vedam, Phys. Rev. 114, 1217 (1959).

L11. Piezoelectric Characteristics of Lead Titanate Zirconate Ceramics at Low Temperatures.* ROBERT GERSON. *Clevite Corporation.*—Piezoelectric and dielectric properties were measured for polarized lead titanate zirconate ceramics between 4.2°K and 77°K. Two types of ceramic were investigated. One was an oxide ferroelectric of normal purity ($Pb_{0.95}Sr_{0.05}Zr_{0.53}Ti_{0.47}O_3$), and the other was modified chemically by an additive of excess valency to lower the coercive field ($PbZr_{0.52}Ti_{0.48}O_3$+1 wt% Nb_2O_5). Both materials were found to retain strong piezoelectric activity in liquid helium. The magnitude of the piezoelectric coupling coefficient k_p dropped to 80% of its room temperature value for the normal ferroelectric in liquid helium while the corresponding ratio was 63% for the modified material. The free dielectric constant for the normal ferroelectric measured at 1 kc was found to increase with temperature in an almost linear fashion, rising from about 380 in liquid helium to 640 in liquid nitrogen and 1300 at room temperature. The modified material showed a somewhat greater increase.

* Supported by the Acoustics Branch, Office of Naval Research.

TUESDAY AFTERNOON AT 2:00

King Hall

(C. HERRING presiding)

DSSP Symposium on New Effects and Techniques

LA1. Appearance and Disappearance of Localized Moments of Iron Group Impurities in Alloys of Varying Electron Concentration. B. T. MATTHIAS, *Bell Telephone Laboratories.* (30 min.)

LA2. Solid-State Optical Masers. C. G. B. GARRETT, *Bell Telephone Laboratories.* (30 min.)

LA3. Tunneling through Thin Insulating Films. J. C. FISHER, *General Electric Research Laboratory.* (30 min.)

LA4. Current Problems in the Statistical Mechanics of Ferromagnetism. R. BROUT, *Cornell University.* (30 min.)

TUESDAY AFTERNOON AT 2:00

Criscuolo Hall

(G. RADO presiding)

Invited Paper

M1. Paramagnetic Resonance of Rare Earth Ions. W. LOW, *The Hebrew University, Jerusalem.* (30 min.)

Electron Spin Resonance, Hyperfine Interactions, Relaxation II

Contributed Papers

M2. Relaxation Mechanisms. R. H. ASENDORF, *Hughes Research Laboratories.*—Various relaxation mechanisms of paramagnetic resonance are examined, using the diagram method. The principal mechanisms to be discussed are the Waller and the Kronig-Van Vleck mechanisms. However, other mechanisms will also be mentioned; ferromagnetic relaxation will be touched upon briefly.

M3. Measurement of Electronic Relaxation Times by Double Resonance Techniques. JAMES J. KREBS, *U. S. Naval Research Laboratory.*—By saturating the forbidden ($\Delta m_S = 1$, $\Delta m_I = \pm 1$) transitions in an electron-nuclear system having a weak static dipole interaction, the NMR signal may be enhanced. It can be shown that the nuclear enhancement $(I - I_0)/I_0$ is a function of the ESR saturation parameter $\gamma_e^2 H_1^2 T_1 T_2$. We have used these facts to measure the electronic T_1 by double resonance techniques. The enhancement of the NMR signal of protons in charred sucrose has been measured both in vacuum as a function of microwave power and at constant microwave power as a function of O_2 pressure over the sample. From these two sets of data it is possible to derive relative values for the product $T_1 T_2$ as a function of O_2 pressure. For a sucrose char prepared at 400°C the electronic T_1 decrease by a factor of 30 on going from vacuum to dry atmospheric air conditions. The results are similar to those of Singer, Spry, and Smith,[1] who used direct saturation methods on related chars. The long relaxation time of these chars permits considerable NMR signal enhancement (>50) at moderate microwave power even at room temperature.

[1] L. S. Singer, W. J. Spry, and W. H. Smith, *Proceedings of the Third Conference on Carbon* (Pergamon Press, New York, 1959), p. 121.

M4. Spin-Lattice Relaxation via Exchange Interactions. M. J. WEBER, L. RIMAI, H. STATZ, AND G. DEMARS, *Raytheon Company.*—An effective spin-lattice relaxation Hamiltonian is derived for paramagnetic ions coupled by exchange interactions of the form $J\mathbf{S}_1 \cdot \mathbf{S}_2$. The theory is developed for iron-group ions and order-of-magnitude calculations of the strength and temperature dependence of possible relaxation mechanisms are made. Since exchange is expected to be very sensitive to lattice displacement, thermal lattice modulation of exchange interactions can be a more important source of relaxation than the crystalline electric field even for small J. For large J where $J\mathbf{S}_1 \cdot \mathbf{S}_2$ is essentially diagonal in the resulting coupled spin representation, the dominant relaxation transitions are induced by time-dependent Moriya-type anisotropic exchange terms arising from a bilinear combination of exchange and spin-orbit interactions. This mechanism has spin operators $\mathbf{S}_1 \times \mathbf{S}_2$ which connect states in different resultant spin multiplets, and therefore the net relaxation involves spin transitions to and from an intermediate state accompanied by the creation and destruction of two direct-process phonons with energies $\sim J$ and an energy difference equal to the microwave resonance transition. Data on the relaxation of exchange-coupled Cr^{3+} ion pairs in Al_2O_3 is presented. The possible influence of exchange systems on the relaxation of isolated paramagnetic ions will be discussed.

M5. Lattice Heating Effects in Spin-Lattice Relaxation Time Measurements.* M. MANDEL, G. E. PAKE AND J. P. GOLDSBOROUGH, *Stanford University.*—In the measurement of paramagnetic relaxation times by CW methods at liquid helium temperatures, one is often faced with the problem of lattice heating.[1] In order to study this effect we have developed a modulated CW method in which the microwave power remains on for a time long compared to that necessary to saturate the electrons, but the duty cycle is such that the average power is not sufficient to appreciably heat the lattice. This method is particularly appropriate in cases of short T_1 for which high rf power is required for saturation. We have applied this technqiue to measure the relaxation time of DPPH. At 300°K both the usual CW and our modulated CW methods give the same result, $T_1 \sim 5 \times 10^{-8}$ sec. However, at 1.5°K, where the lattice specific heat is very small, CW saturation[2] and the recovery time of M_z from a high power pulse[3] give a T_1 of $\sim 10^{-6}$ sec, while our modulated CW method gives $T_1 \sim 10^{-8}$ sec. Similar decreases in apparent T_1 of $Cu(SO_4) \cdot 5H_2O$ on reducing the average power have been observed in this laboratory by R. B. Griffiths and R. H. Webb.

* Work supported by the U. S. Air Force Office of Scientific Research.
[1] M. W. P. Strandberg, Phys. Rev. 110, 65 (1958).
[2] J. P. Goldsborough, M. Mandel, and G. E. Pake, Phys. Rev. Letters 4, 13 (1960).
[3] James W. Meyer, thesis, Massachusetts Institute of Technology (unpublished).

M6. Linewidths in the Paramagnetic Resonance of Mn^{++} in Aqueous Solution. ROBERT G. HAYES AND ROLLIE J. MYERS, *University of California and Lawrence Radiation Laboratory, Berkeley.*—Two interesting effects are observed in the widths of the six hyperfine components for an Mn^{++} solution when it is heated to above room temperature. Just slightly above room temperature it becomes quite apparent that the hyperfine components have different widths. The outer lines are the widest and the inner are the narrowest, but the widths are not exactly symmetric with respect to the center of the hyperfine pattern. These effects are due not to incomplete averaging of any anisotropic hyperfine splitting but to an incomplete Paschen-Back effect in the isotropic terms of the Hamiltonian of a ^6S ion. Each hyperfine line is a rough superposition of five transitions, and the splittings within the groups of five depend upon second-order terms involving the hyperfine interaction. At temperatures below 80°C the widths of the hyperfine components decrease with increasing temperature. This is in agreement with that expected for the tumbling of a hydrated ion, but at higher temperatures the widths are observed to increase with increasing temperature. Our observations are in general agreement with those of Avvakumov *et al.*,[1] but our interpretation of the temperature effects is quite different.

[1] V. I. Avvakumov, N. S. Garif'yanov, B. M. Kozyrev, and P. G. Tishkov, J. Exptl. Theoret. Phys. (U.S.S.R.) 37, 1564 (1959).

M7. ESR Linewidths in Dilute Paramagnetic Solutions at *K* and *X* Bands.* A. W. NOLLE AND L. O. MORGAN, *The University of Texas.*—Electron spin resonance linewidths for $Mn(H_2O)_6^{++}$ in very dilute solution (0.001–0.02 M) and at 300°K decrease with increasing microwave frequency. Widths for individual hyperfine components at 24 kMc are approximately 75% of those measured at 9.4 kMc. This is in quantitative agreement with predictions of Bloembergen and Morgan,[1] which were based on the observed behavior of the proton-phase memory-relaxation time as a function of frequency in similar solutions. Other effects of the frequency increase are an observed decrease of about 9% in the spacing of hyperfine components, and the appearance of asymmetry in the line shape. In solutions of $Cu(ethylenediamine)_2^{++}$, for which the g value is anisotropic, the hyperfine separation remains nearly constant, but the (nonidentical) lines broaden with increasing microwave frequency.

* Supported in part by the Robert A. Welch Foundation.
[1] N. Bloembergen and L. O. Morgan, J. Chem. Phys. 34, 842 (1961).

M8. The Hyperfine Interaction of Europium. W. E. BLUMBERG AND J. EISINGER, *Bell Telephone Laboratories.*—We have studied the microwave and electron-nuclear double resonance (ENDOR) spectrum of Eu^{++} in CaF_2 at 1.3°K. The sign of the hyperfine interaction A was found to be negative. We list

below the approximate measured values of $A(Eu^{151})$ in several electronic states $A(4f^76s6p) = +1000$ Mc/sec[1]; $A(4f^76s^2) = -20$ Mc/sec[2]; $A(4f^7) = -100$ Mc/sec. The large positive A for the excited atom can be attributed mainly to the $6s$ electron. The origin of negative A in $Eu^{++}(4f^7)$ is probably polarization of the inner s selectrons by the f electrons. While this effect must also be present in atomic $Eu(4f^76s^2)$, it appears to be reduced by the presence of the closed $6s$ shell. This indicates that the polarization induced in the $6s$ shell by the half-filled $4f$ shell contributes about $+80$ Mc/sec to the total hyperfine interaction corresponding to about 0.08 Bohr magneton. The ENDOR transitions $\Delta m_J = 0$, $\Delta m_I = \pm 1$ for all m_J substrates were observed with widths of about 130 *kc*. These narrow lines yield precise values of the hyperfine interaction, the quadrupole interaction and the enhancement of the applied field at the nucleus. From these results the hyperfine structure anomaly Δ of Eu^{151} and Eu^{153} may be obtained for this state.

[1] K. Krebs and R. Winkler, Ann. Phys. **20**, 60 (1957).
[2] P. G. H. Sanders and G. K. Woodgate, Proc. Roy. Soc. (London) **A257** 269 (1960).

M9. Electron-Nuclear Double Resonance of Tetravalent Pa^{231}.* H. J. STAPLETON, J. D. AXE, AND C. D. JEFFRIES, *University of California, Berkeley.*—The earlier paramagnetic resonance hyperfine structure measurements[1] on tetravalent Pa^{231} in $Cs_2(Pa,Zr)Cl_6$ at 9 kMc and 4.2°K have been extended to higher precision by the ENDOR technique. The electron g factor and nuclear g factor are found to have opposite signs. Assuming that the sign of the latter is positive, as indicated by the nuclear shell model, we find for the constants in an isotropic spin Hamiltonian: $S = \frac{1}{2}$; $I = \frac{3}{2}$; $g = -1.1423 \pm 0.0014$; $|A|/h = 1578.6 \pm 1.4$ Mc/sec; and $\mu(Pa^{231}) = 1.96 \pm 0.02$ nm, including a 9% correction due to perturbations from a crystal field level 1900 cm^{-1} above the ground state. Weak ($\sim$0.5 Mc/sec) hyperfine coupling between Cs^{133} and Pa^{231} has also been detected.

* Supported in part by the U. S. Atomic Energy Commission and the Office of Naval Research.
[1] J. D. Axe, R. Kyi, and H. J. Stapleton, J. Chem. Phys. **32**, 1261 (1960)

M10. Spin and Moment Determination of Cd^{109} by Optical Double Resonance.* M. N. MCDERMOTT AND R. NOVICK, *Columbia University.*—The spin and nuclear moments of Cd^{109} (475*d*) have been determined by the optical double-resonance technique. An isotopically pure sample was prepared by proton bombardment of silver. Radio frequency resonances in the $^3P_1$ state were detected by a change in the polarization of scattered 3261-A cadmium resonance radiation. The spin was determined to be $I = \frac{5}{2}$ from a study of the low-field Zeeman resonances. The hyperfine structure has been determined by observing the transitions $\Delta F = 0$, $\Delta m_F = \pm 1$ at magnetic fields sufficiently large to resolve the individual Zeeman lines. The intervals so obtained are $f(\frac{7}{2} \leftrightarrow \frac{5}{2}) = 4204 \pm 20$ Mc and $1(\frac{5}{2} \leftrightarrow \frac{3}{2}) = 2610 \pm 35$ Mc/sec. The hyperfine interaction constants derived from these intervals are $A(^3P_1) = -1149 \pm 6$ Mc/sec and $B(^3P_1) = -174 \pm 17$ Mc/sec. An incomplete analysis gives $\mu_I = -0.829 \pm 0.005$ nm and $Q = +0.80 \pm 0.20$ b. The ordering of the hyperfine levels (and thus the sign of μ_I) was unambiguously determined by utilizing circularly polarized exciting radiation.

* Work supported in part by a contract with the U. S. Air Force monitored by the Air Force Office of Scientific Research.

M11. Hyperfine Structure of the ^3P States of Be^9. ALLEN LURIO AND A. G. BLACHMAN, *IBM Watson Laboratory.*—The hfs of Be^9 ($I = \frac{3}{2}$) in its metastable $^3P_2$ and $^3P_1$ atomic states has been measured with greater precision by the atomic-beam magnetic-resonance method. The hfs intervals in the $^3P_2$ state are $\Delta\nu(\frac{5}{2},\frac{3}{2}) = 435.483 \pm 0.020$ Mc/sec, $\Delta\nu(\frac{3}{2},\frac{1}{2}) = 312.019 \pm 0.020$ Mc/sec, and $\Delta\nu(\frac{1}{2},\frac{1}{2}) = 187.611 \pm 0.20$ Mc/sec. The hfs intervals in the $^3P_1$ state are $\Delta\nu(\frac{5}{2},\frac{3}{2}) = 354.415 \pm 0.020$ Mc/sec and $\Delta\nu(\frac{3}{2},\frac{1}{2}) = 202.950 \pm 0.020$ Mc/sec. In order to obtain the dipole and quadrupole coupling constants from the hfs separations, second-order corrections arising from off- diagonal matrix elements of the hyperfine interaction between the ^3P fine-structure levels must be included. After these corrections are made, the values for the dipole and quadrupole interaction constants are $a(^3P_2) = -124.536$ Mc/sec, $b(^3P_2) = 1.433$ Mc/sec, $a(^3P_1) = -139.408$ Mc/sec, and $b(^3P_1) = -0.927$ Mc/sec. If the second-order corrections are neglected, then $a(^3P_2) = -124.617$ Mc/sec, $b(^3P_2) = 0.775$ Mc/sec, $a(^3P_1) = -140.150$ Mc/sec and $b(^3P_1) = -3.233$ Mc/sec. The theoretical ratio of the b coefficients for unperturbed states should be $b(^3P_2)/b(^3P_1) = -2$. The second-order corrections (which greatly improve the agreement with theory) depend on the ^3P fine-structure separations, and until these separations are known more precisely we cannot state with confidence the quadrupole moment or the source of the remaining discrepancy in the b ratio.

M12. Electron Spin Resonance in Semiconducting Diamond.* M. DRAKE BELL AND WILLIAM J. LEIVO, *Oklahoma State University.*—Three semiconducting diamonds which were previously studied with respect to optical and electrical properties are being investigated by electron spin-resonance techniques. The p-type diamonds have resistivities of the order of 100 ohm cm. Two different spin-resonance spectra were obtained at room temperature. In an intensely blue diamond a resonance line of moderate strength occurred with a g value near 2. A second, partially blue diamond showing strong photoconductivity maxima in the visible and unusual red luminescence gave a broad, as yet unresolved resonance different from that of the intensely blue diamond. A good, definable spectrum could not be obtained in the third specimen. Spectra were also obtained on nonconducting diamonds. The spectrum obtained from the intensely blue semiconducting diamond differs from the spectra observed in diamonds containing nitrogen, as has been reported previously by the IBM group.[1] Optical measurements show that nitrogen is not present in these semiconducting diamonds; however, free carriers are present; also, photoconductivity and lifetime measurements show that there are imperfections which could conceivably exhibit spin resonance.

* This research was supported by the U. S. Air Force Office of Scientific Research.
[1] W. V. Smith, P. P. Sorokin, I. L. Gelles, and G. L. Lasher, Phys. Rev. **115**, 1546 (1959).

TUESDAY EVENING AT 7:30

(Cocktails from 6:00)

Bali Room, Herrmann Hall

(F. SEITZ presiding)

Banquet of the American Physical Society

After-dinner speech: **Traffic—Old and New.** ROBERT HERMAN, *General Motors Corporation.*

WEDNESDAY MORNING AT 9:30

421 Spanagel Hall

(DAVID W. MCCALL presiding)

High-Polymer Physics III

MA1. Effects of Electron-Irradiation on the Secondary Dielectric Dispersions in Nylon 6-6 and Nylon 6-10.† M. N. STEIN AND R. G. LAUTTMAN, *U. S. Army Signal Research and Development Laboratory* AND J. A. SAUER AND A. E. WOODWARD, *The Pennsylvania State University.*—The effects of electron irradiation at doses from 25 mr to 1000 mr and of thermal treatment on the dielectric properties of nylon 6-6 and nylon 6-10 have been studied in the temperature region from −160 to 80°C from 0.1 to 100 kc. For both polymers, the radiation produces significant changes in each of the two secondary dielectric dispersions which are observed over the temperature region investigated. It is found that a post-irradiation annealing at about 80°C will restore the values of the dielectric loss associated with the lowest temperature dielectric dispersion to approximately the original non-irradiated values. Significant changes are also produced by subsequent annealing in the magnitude of the dielectric loss of the next higher temperature dispersion occurring in the region just below or near 0°C. The changes observed in the dielectric properties are interpreted in terms of the alteration in structure produced by irradiation, absorbed moisture and thermal treatment. The concept of radiation damage as a thermal spike phenomenon is introduced to aid in the understanding of the combined effects of thermal quenching and irradiation.

† Supported in part by the U. S. Atomic Energy Commission.

MA2. Secondary Dielectric Dispersions in Nylon 6-6 and Nylon 6-10.† R. G. LAUTTMAN AND M. N. STEIN, *U. S. Army Signal Research and Development Laboratory* AND J. A. SAUER, *The Pennsylvania State University.*—A vacuum dielectric cell has been designed and constructed for measurements of the dielectric constant and the dielectric loss of polymeric materials. This cell has been used to measure the dielectric behavior of films of polyhexamethylene adipamide and polyhexamethylene sebacamide over the temperature region from −160 to 80°C for frequencies from 0.1 to 100 kc. The effects of moisture and of thermal treatment on the dielectric behavior of the nylon films have been explored. For both polymers the dielectric data show two low-temperature dispersion regions. Activation energies for the relaxation processes involved have been estimated. Comparison of results is made with other dielectric data which do not extend to such low temperatures and to dynamic mechanical data.

† Supported in part by the National Science Foundation and the U. S. Atomic Energy Commission.

MA3. Ultrasonic Measurements on Polymer Solutions under Hydrostatic Pressure. W. PHILIPPOFF, *Esso Reserach and Engineering Company* (introduced by John Rehner).—Solutions of polymer in oil are widely used as motor lubricants and, as such, are subjected in the engine bearings to a combined effect of high hydrostatic pressures and rates of shear in the millions sec^{-1}. A combination of ultrasonic vibrations and hydrostatic pressure could simulate the condition in bearings and, in addition, could afford a test for Ferry's theory, which involves the idea of the free volume. A cylindrical quartz crystal was excited in resonance torsional vibration at 19.5 kc in the polymer-containing oil; which was subjected to hydrostatic pressures up to 1000 atm and over a temperature range from 25 to 55°C. The solvent (oil) behaves under these conditions as a pure liquid, the viscosity of which increases exponentially with pressure up to about tenfold. The relative viscosity (η/η_0) of the polymer blend is very little affected by the hydrostatic pressure but the increase in η_3 (elastic component) is proportionately smaller than the increase in viscosity of the solvent. The measurements are combined using the method of reduced variables and compared with measurements at atmospheric pressure and different temperatures using two different crystals at 19.5 and 58 kc, and give a single reduced curve for all temperatures, frequencies, and hydrostatic pressures. This is then compared with steady-state (capillary) measurements.

MA4. Dependence of Transition Points on the Structure of Cholesteryl Esters. JAMES L. FERGASON, *Westinghouse Research Laboratories.*—A series of materials which exhibit the cholesteric mesomorphic phase have been studied with the particular goal of observing the effect of the molecular structure of melting point, clearing point, and morphology. In the mesomorphic phase these materials exhibit a strong optical rotatory dispersion and a strong scattering which is dependent on the angle of incidence, the sense of rotary polarization, and the wavelength of the incident beam of light. A detailed study of the effect of molecular structure on melting point and clearing point has been made using chloesteryl esters of aliphatic acids and cholesteryl carbonates of aliphatic alcohols. The results from approximately 35 compounds will be reported, and the results discussed on the basis of their relation to other cholesteric liquid crystals.

MA5. Empirical Relation of the Expansion Coefficient to Activation Parameters of Certain Polymer Relaxations. R. K. EBY, *du Pont Experimental Station* (introduced by N. G. McCrum).—Experimental data obtained from dynamic mechanical observations of relaxations in a number of partially crystalline and completely amorphous polymers are collected and analyzed to determine the activation enthalpies and entropies. Values of the isobaric coefficient of thermal volume expansion are also collected for polymers which are as nearly as possible of the same composition and state. These data are analyzed to show that polymer relaxations appear to obey some of the empirical relations which describe activated processes in inorganic solids.[1,2] This result raises certain questions which are discussed togehter with the experiments which they suggest. Attention is also called to experiments which are needed to verify additional relationships.

[1] A. W. Lawson, J. Phys. Chem. Solids 3, 155 (1957).
[2] R. W. Keyes, J. Chem. Phys. 29, 467 (1958).

MA6. Orientation in Cold Rolled Polypropylene. ZIGMOND W. WILCHINSKY, *Esso Research Center.*—Sheets of isotactic polypropylene cold rolled in one direction to one-half the initial thickness, showed a preferred orientation of the fiber axis (i.e., *c* axis) inclined to the rolling direction and to the plane of the sheet. In general there were two directions of preferred orientation, at inclinations of about +30° and −30°. There was no pronounced orientation of the *b* axis (which is perpendicular to the *c* axis). The nature of this orientation differs from that reported for extruded film where it was found that the *b* axis is preferentially oriented perpendicular to the surface and the *c* axis is preferentially oriented in the extrusion direction (in the plane of the film). A mechanism of deformation during rolling is proposed.

MA7. A Study of Cracking and Fracturing of Spherulitic Isotactic Polypropylene. LEO BARISH, *Fabric Research Laboratories, Inc.* (introduced by D. W. McCall).—Isotactic polypropylene was melted and crystallized at 125°C. Crystallization was observed dynamically on a microscopic heating stage. The observations showed the spherulitic induction period to occur over a relatively long time. Spherulites, when first formed, appear to have a lower order of birefringence than after some growth. Positive and negative spherulites are conceived with specific characteristics which are propagated with growth. Between 4–4.5 min crystallization cracking occurs between spherulitic boundaries. In a parallel experiment samples crystallized at 125°C were quenched after different degrees of spherulization. The effect of degree of spherulization on stress-strain properties was studied and the necks and fractures of the samples studied. The completely spherulitic samples broke abruptly at spherulitic boundaries without necking. The rate of elongation affected the nature of the fracture of completely spherulitic samples. At low rates of elongation the spherulites have a tendency to "pull out" at the fracture. At high rates of elongation the spherulites break more sharply at their boundaries.

MA8. Ion Exchange Kinetics of Polyelectrolytes under Steady State Electrolysis Conditions with a Porous Frit.* STANLEY J. GILL AND GUY FERRY, *University of Colorado* (introduced by D. W. McCall).—A theory for measuring rate constants of the reaction between free small ions and bound small ions with polyelectrolytes is presented. The general theoretical approach is similar to that given by Wall and Greiger.[1] However, we have considered the solution of the electrolysis exchange equations with boundary conditions which would conform to a steady-state situation, such as one obtains in determining diffusion constants by the porous frit method.[2] With these conditions considerable simplification results. The theoretical results suggest the experimental determination of the ratio of tagged ion flows across similar frits towards anode and cathode as a function of different current conditions. For a one exchange constant theory, this ratio of flows follows a simple exponential equation. The chief variables for experimentation are the electrolysis current and the thickness of the frit. These two parameters determine the time of exposure that the polyelectrolyte bound ions react with unbound ions. A two-exchange constant theory is also theoretically tractable for steady-state boundary conditions.

* Supported in part by the National Cancer Institute.
[1] F. T. Wall and P. F. Grieger, J. Chem. Phys. 20, 1200 (1952)
[2] A. R. Gordon, Ann. N. Y. Acad. Sci. 46, 285 (1945).

MA9. Intrinsic Viscosity of Fractions of Isotactic Poly (Methyl Methacrylate). SONJA KRAUSE AND ELIZABETH COHN-GINSBERG, *Rohm and Haas Company.*—The intrinsic viscosities of fractions of isotactic poly(methyl methacrylate) having $\bar{M}_w/\bar{M}_n = 1.4$ have been measured in several solvents. These intrinsic viscosities will be compared with those of fractions of a poly(methyl methacrylate) sample polymerized free-radically at 60°C. In benzene and acetone solution, the intrinsic viscosities of the isotactic fractions are appreciably higher than those of fractions of the free-radically polymerized sample of comparable $\bar{M}_w$.

MA10. Swelling of Unfilled and Highly Filled Polymers. K. W. BILLS, JR., AND F. S. SALCEDO, *Aerojet-General Corporation.*—The swelling of polymers in solvents is a useful method for determining the effective crosslinking of the polymer structure. However, it is now shown that this method may be applied satisfactorily to solid composite propellants and other high-filled polymers. A unique method has been devised for the accurate measurement of the swelling ratio of the gel phase of a solid propellant. The method is based on the observation that the binder-filler bond, for most filler particles, releases on swelling. The binder around the particle swells leaving a hollow pocket which becomes filled with solvent. Corrections for this "waste" solvent and for the volume of filler lead to the equations from which the swelling of the polymer can be calculated. Experimental verification is given for several filled systems.

WEDNESDAY MORNING AT 9:30

Ballroom, Herrman Hall

(A. F. KIP presiding)

Metals

N1. Image of the Fermi Surface in Phonon and Spin Wave Dispersion Curves. E. J. WOLL AND S. J. NETTEL (introduced by W. Kohn), *University of California, San Diego.*—"Kinks" are expected to show up in phonon and spin wave dispersion curves in metals when the wave vector differs from a diameter of the Fermi surface by a reciprocal lattice vector.[1] Hence, the locus of the kinks in k-space yields directly the shape of the Fermi surface. The kinks arise because part or all of the basic interaction is caused by virtual excitation of electron-hole pairs. Approximate calculations of their magnitudes have been made. For phonons the kinks turn out to be unexpectedly small. For spin waves in rare earth metals they are larger. Neutron diffraction measurements of spin wave dispersion curves carried out to a few percent accuracy should display an image of the Fermi surface.

[1] W. Kohn, Phys. Rev. Letters 2, 393 (1959). Strictly speaking these kinks are logarithmic infinities of the slope.

N2. Observation of Four Types of Hall Constant Anisotropy in Copper and Their Role in the Determination of the Fermi Surface. J. E. KUNZLER AND J. R. KLAUDER, *Bell Telephone Laboratories.*—Four of five possible types of high-field Hall constant anistropy predicted for metals[1] have been observed by us in copper and will be discussed. The fifth type is not expected for copper. The observed Hall constant behavior is markedly different from the results previously reported, primarily due to our use of samples that were both single crystals and highly pure ($R_{273°K}/R_{4.2°K}$ as large as 8000). Generally, when the magneto-resistance saturates, the Hall constant can be directly related to the Fermi surface shape; the essential conditions will be summarized and several Hall constant calculations, using the Pippard model, are compared with the corresponding experimental values. Finally, the utility of Hall voltage data for distinguishing between different possible Fermi surface topologies will be illustrated for the first time.

[1] I. Lifshitz, and V. Peschanskii, J. Exptl. Theoret. Phys. (USSR) 35, 1251, 1958 (translation: Soviet Phys.—JETP 8, 875, 1959).

N3. Cyclotron Resonance Effects in Zinc. J. K. GALT AND F. R. MERRITT, *Bell Telephone Laboratories.*—Earlier observations of cyclotron resonance in zinc[1] have been extended to a broad range of crystallographic orientations. For the samples used here, $R_{300°K}/R_{4.2°K}$ is 30 000 or higher, and the observations were all made at 72 000 Mc/sec and at 1.3°K with the magnetic field in the plane of the sample. When $B_{D.C.}$ is parallel to $\langle 11\bar{2}0\rangle$, effective masses of 0.54 m_0 and 0.42 m_0 are observed. There is some evidence that other, smaller signals corresponding to slightly different masses are also present. As $B_{D.C.}$ rotates toward parallelism with $\langle 0001\rangle$, the signal corresponding to a mass of 0.42 m_0 disappears after a rotation of about 25°, and the 0.54 m_0 mass increases. When $B_{D.C.}$ is about 10° from $\langle 0001\rangle$, two masses are observed again, 1.5 m_0 and 1.3 m_0. When $B_{D.C.}$ is precisely parallel to $\langle 0001\rangle$, only one mass, 1.3 m_0, is observed. When $B_{D.C.}$ is parallel to $\langle 10\bar{1}0\rangle$, a mass of 0.54 m_0 is observed, again with some evidence for other, smaller, signals corresponding to slightly different masses. As $B_{D.C.}$ rotates from $\langle 10\bar{1}0\rangle$ toward parallelism with $\langle 0001\rangle$, the 0.54 m_0 mass increases, and in the neighborhood of $\langle 0001\rangle$ results similar to those mentioned above for this region are obtained.

[1] J. K. Galt, F. R. Merritt, W. A. Yager, and H. W. Dail, Phys. Rev. Letters 2, 292 (1959).

N4. The de Haas-van Alphen Effect in Calcium.* J. H. CONDON† AND J. A. MARCUS, *Northwestern University.*—The de Haas-van Alphen effect in calcium has been observed at 1.3°K by measuring the couple on a single crystal in a uniform magnetic field. The dominant period, $P=2.9\times10^{-7}$ gauss^{-1} is approximately five times that observed by Berlincourt[1] on the same crystal using the pulsed field technique. At 19.5 kgauss the amplitude of the oscillations in $\Delta\chi$ is $\sim10^{-11}$ per g. The oscillating couple was recorded directly by a servo-type torsion balance having a sensitivity of 2.5×10^{-4} d cm/mm. We are indebted to Dr. Berlincourt for making available to us the calcium crystal grown by Dr. McCreary.[2]

* Supported by the National Science Foundation and the Advanced Research Projects Agency of the U. S. Department of Defense.
† National Science Foundation Fellow.
[1] T. G. Berlincourt, Programme of the Seventh International Conference Low Temperature Physics, Toronto, 1960, p. 158.
[2] W. J. McCreary, J. Metals 10, 615 (1958).

N5. Magnetoacoustic Attenuation in Indium Single Crystals. J. A. RAYNE AND B. S. CHANDRASEKHAR, *Westinghouse Research Laboratories.*—The magnetic field dependence of ultrasonic attenuation in single crystals of indium has been studied at 4.2°K and a frequency of 75.5 Mc. An oscillatory dependence, periodic in $1/H$, has been observed for longitudinal modes in the [001], [100], and [110] directions, the magnetic field H in all cases being perpendicular to the sound propagation direction. The results will be discussed on the basis of a nearly free electron model for the Fermi surface in indium. A similar model has been applied with conspicuous success to several other metals.[1]

[1] For a review, see W. A. Harrison, Phys. Rev. 118, 1190 (1960).

N6. Magnetoresistance of Lithium Metal Crystals.* R. BOWERS, *Cornell University.*—We have cooled to 4°K some lithium which was single crystal at room temperature and measured its transverse magnetoresistance at 4°K. We hope to obtain some measure of the anisotropy of the Fermi surface. The residual resistance ratio ($\rho_{300}/\rho_{4°K}$) of the material was 500 and the maximum magnetic field used was 13 000 gauss ($\omega\tau\sim0.4$). The current direction was $\langle 100\rangle$ with respect to the original crystal. The transverse magnetoresistance ρ_H/ρ_0 was found to be 1.2 under these conditions. No anisotropy in ρ_H has been detected greater than 1% of ρ_H (or 5% of $(\Delta\rho)_H$). The magnetoresistance is approximately linear with respect to the magnetic field. The extent of the martensitic transformation[1] in these particular specimens and its effect on the results is not yet established. The orientation of the martensitic phase with respect to the host crystal will be discussed. We expect to measure the longitudinal magnetoresistance in this material. Our experience in growing lithium single crystals by the Czochralski method will be discussed.

* Supported by the U. S. Atomic Energy Commission and the Advanced Research Projects Agency.
[1] C. S. Barrett Phys. Rev. 72, 245 (1947).

N7. Magnetoresistance in Metals with Small Energy Gaps.* M. H. COHEN AND L. M. FALICOV, *Institute for the Study of Metals, University of Chicago.*—When the presence of energy gaps in the band structure of a metal changes the topology of the Fermi surface giving rise to the existence of "open" orbits it is well known that the transverse magnetoresistance, which would saturate for high fields otherwise, increases unboundly as H^2. However, when the energy gaps are small compared with the magnetic splitting ($\epsilon_G<\hbar\omega_c$), the periodic potential which results from the lattice can be considered as a perturbation which gives rise to small transition probabilities between various magnetic levels. The solution of the quantum mechanical transport equation applied to simple models in this limiting case shows that as H increases, the magnetoresistance tends again to a saturation value, i.e., the electrons describe "closed" orbits in k-space. Thus, the transverse magnetoresistance of metals with "open" orbits as a function of magnetic field should increase quadratically for high fields in the region $\hbar\omega_c<\epsilon_G$ but decrease towards a constant value when $\hbar\omega_c>\epsilon_G$. We call this phenomenon *magnetic breakdown.*

* Supported in part by the Office of Naval Research.

N8. Calculation of the Band Structure of Silver. B. SEGALL, *General Electric Research Laboratory.*—Added interest attaches to a band calculation of one of the noble metals because their Fermi surfaces have been more thoroughly determined than those for other metals. De Haas-van Alphen measurements[1] have shown that the Fermi surfaces of these metals are roughly spherical except for "necks" in the [111] directions which contact the zone surfaces. A band calculation for silver has been carried out by the Green's function method. The potential has been constructed using Ag^+ Hartree functions renormalized in the equivalent sphere. The energy bands are qualitatively very similar to those obtained for copper by the same method.[2] The energy gap at the hexagonal zone surface, which is approximately 4.2 ev, is comparable to (although somewhat smaller than) the large gap found for copper. The level ordering with the p-level lower than the s-level is the same. From the depression of the conduction band in the [111] direction relative to the other directions, it appears probable that the calculated bands are consistent with a Fermi surface making contact with the hexagonal zone surface.

[1] D. Shoenberg, Phil. Mag. 5, 105 (1960).
[2] B. Segall, Bull. Am. Phys. Soc. 6, 10 (1961).

N9. Knight Shift Calculation for Be. FREDERICK J. MILFORD, *Battelle Memorial Institute.*—Jacques[1] has carried out an augmented plane wave calculation of the electronic wave functions in metallic Be. This calculation has been done in a spherical approximation, i.e., neglecting the actual shape of the atomic polyhedron, and uses an approximate potential constructed from powers of the radius in such a way that the radial wave functions may be expressed as confluent hypergeometric functions. Jacques work can be readily extended to calculate P_J, the probability density of a conduction electron at the nucleus averaged over states at the Fermi surface. We

have done this and obtained the numerical value $P_f=0.43a_0^{-3}$. This P_f when combined with $\Omega=54a_0^3$ for the atomic volume and $\chi_p=2\times10^{-7}$ cgs volume units gives $\Delta H/H=0.0039\%$ (theoret). This compares with other theoretical values and experiment as follows:

	$\Delta H/H$ (exp) (%)	P_f (theoret)	$\Delta H/H$ (theoret) (%)
Townes, Herring and Knight[2]	<0.002	$0.50a_0^{-3}$	0.0045
Knight[3]	0.000		
Pomerantz and Das[4]		$1.03a_0^{-3}$	0.0114
Milford and Gager	<0.001	$0.43a_0^{-3}$	0.0039

[1] R. Jacques, Cahier Phys. **No. 70**, 1 (1956); *ibid.*, **Nos. 71–72**, 31 (1956).
[2] C. H. Townes, C. Herring, and W. D. Knight, Phys. Rev. **77**, 852 (1950).
[3] W. D. Knight, *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic Press, Inc., New York, 1956), Vol. 2, p. 93.
[4] M. Pomerantz and T. P. Das, Phys. Rev. **119**, 70 (1960).

N10. Interband Transitions in Metals. M. S. DRESSELHAUS AND G. F. DRESSELHAUS, *Lincoln Laboratory,* M.I.T.*—Recently, a resonant absorption of infrared radiation has been observed in Bi upon application of a static magnetic field.[1] The resonant behavior was attributed to interband transitions from Landau levels in the valence band to those in the conduction band. To interpret this experiment, a calculation of the line shape for direct interband transitions in a metal has been carried out, both in the presence of a static magnetic field H and for $H=0$. The result obtained for a metal is qualitatively different from that in a semiconductor because of the position of the Fermi energy in the conduction band and because of the free carrier absorption in a metal. The connection between these interband effects and the band structure of the metal is discussed.

* Operated with support from the U. S. Army, Navy, and Air Force.
[1] R. N. Brown, J. G. Mavroides, M. S. Dresselhaus, and B. Lax, Phys. Rev. Letters **5**, 243 (1960).

N11. Photoelectric Interband Absorption in a Single Crystal of Silver.* T. N. RHODIN AND A. T. FROMHOLD, JR., *Cornell University.*—The optical constants of a single crystal of silver were determined in the region where interband absorption is important. The relative attenuation and phase-change introduced by reflection of polarized light were measured and the optical constants and reflectivities computed. The crystal was mechanically polished parallel to the (111) face, electropolished, and annealed at 600°C at 1×10^{-8} mm Hg. The measurements were made at 5×10^{-9} mm Hg. The photoelectric absorption edge was found to occur at 3500 A; the data of Schulz[1] for polycrystalline material showed the photoelectric absorption edge to occur at 3300 A. The model of Suffczynski[2] for photoelectric interband absorption in the noble metals is used to obtain the relationship between the experimental dispersion curves and the shape of the Fermi surface, the energy gap, the electron effective masses in the energy bands, and an average interband transition matrix element. Similar optical measurements are planned for copper-zinc alloys.

* This grant was supported by the United States Steel Corporation and the Advanced Research Projects Agency.
[1] L. G. Schulz, *Advances in Physics*, edited by N. F. Mott (Taylor and Francis, Ltd., London, 1957), Vol. 6, p. 134.
[2] M. Suffczynski, Phys. Rev. **117**, 663 (1960).

N12. Thermoelectric Power of Copper Alloys.* F. J. BLATT, M. GARBER, AND B. W. SCOTT, *Michigan State University.*—We have measured the thermoelectric power relative to pure copper of various dilute copper base alloys containing silver and gold. The measurements extend over the temperature range from 8 to 350°K. The alloys were prepared by melting the constituents in a vacuum induction furnace and chill casting in vacuum. The results of our measurements are analyzed following the procedure adopted by Blatt and Kropschot, and provide additional support for the hypothesis that the maximum in the thermoelectric power of pure copper near 70°K is the result of a phonon-drag mechanism.

* Supported by the Office of Ordnance Research, U. S. Army.

N13. Low-Temperature Resistance Minima and Negative Magnetoresistivities in Dilute Ti-Mn Alloys.* R. R. HAKE, D. H. LESLIE, AND T. G. BERLINCOURT, *Atomics International.*—Negative temperature coefficients of resistivity and *negative* transverse magnetoresistivities have been observed at liquid helium temperatures in quenched hcp Ti alloys containing nominal Mn concentrations, $c(a/o)$, between 0.02 and 2. No resistivity maxima were observed, although for alloys with $c\geq0.21$ the onset of filamentary superconductivity at $T_s\approx2.8$°K could have obscured such behavior at $T<T_s$. $\Delta\rho(T)\equiv\rho(H=30$ kgauss, $T)-\rho(H=0, T)$ increases monotonically in absolute value with c, and for a given c, $|\Delta\rho(T)|$ increases as T decreases for $T_s<T<4.2$°K. For two specimens measured above 4.2°K [$c=0.11$, $\rho(4.2°K)=2.8$ μohm-cm; $c=1.1$, $\rho(4.2°K)=8.2$ μohm-cm)], $[\rho(4.2°K)-\rho(T_{min}\approx16°K)]/\rho(4.2°K)\approx+0.012$ and $\Delta\rho(4.2°K)/\rho(4.2°K)\approx-0.05$. These results suggest that Mn ions in dilute solution in Ti possess magnetic moments which interact with the conduction electrons.[1] Preliminary results on hcp Ti alloys containing $\approx1a/o$ of Cr, Fe, Co, and Ni reveal only small positive magnetoresistivities

$$[\Delta\rho(4.2°K)/\rho(4.2°K)\approx+0.005].$$

* Supported by the U. S. Atomic Energy Commission.
[1] B. T. Matthias, M. Peter, H. J. Williams, A. M. Clogston, E. Corenzwit, and R. C. Sherwood, Phys. Rev. Letters **5**, 542 (1960).

N14. Resistance Anomaly in β-Tungsten Compounds.* C. D. CODY, J. J. HANAK, AND G. T. MCCONVILLE, *RCA Laboratories* (introduced by B. Abeles).—Resistivity measurements have been made on Nb_3Sn, Ta_3Sn, and V_3Sn from 400° to 4.2°K. Several sintered specimens, and for Nb_3Sn, a non-sintered specimen were examined. The results for all specimens were qualitatively similar. With decreasing temperature, the resistance departs from a linear dependence on T, drops rapidly to a constant value and finally reaches the superconducting transition. Since a variety of specimens have been examined, it appears that these results are characteristic of these compounds and not of their preparation. One can represent the data for all specimens by a residual resistivity, a linear ideal resistance, and an additional resistance that is zero at 0°K, and saturates between 150° and 200°K. The additional resistance is of the form suggested by Elliott[1] for the elastic scattering of conduction electrons by orbitals split by the crystalline field. The splitting, as determined by the fit to the data, is 137°, 114°, and 174°K for Nb_3Sn, Ta_3Sn, and V_3Sn. The ratio of the ideal room temperature resistivity to the additional resistivity is 1.4, 1.4, and 1.0, respectively.

* This work was supported by the U. S. Air Force under a Wright Air Development Center contract.
[1] R. J. Elliott, Phys. Rev. **94**, 564 (1954).

WEDNESDAY MORNING AT 10:00

Criscuolo Hall

(G. WANNIER presiding)

Excitons, Band Edges

NA1. Efficiency of Production of Intrinsic Recombination Radiation. J. R. HAYNES, M. LAX, AND W. F. FLOOD, *Bell Telephone Laboratories, Inc.*—Intrinsic recombination radiation efficiency $E \equiv R/(R+P)$, where R is the number of excess electron-hole pairs which recombine with photon emission and P is the number that recombine with phonon emission only. E is shown to be a function of the resistivity of the silicon specimen, its temperature, carrier lifetime, and excess carrier density. Quantitative calculations of E are obtained using experimentally determined values of the radiative lifetime of excitons (6.5×10^{-5} sec), the exciton binding energy (0.008 ev), and the radiative recombination rate of free electrons and holes ($\sigma v = 5\times10^{-15}$ cm^3 sec^{-1}). Comparison of these calculated values will be made with those obtained by direct experiment.

NA2. Photoemission from the Space Charge Region of a Semiconductor. DAVID REDFIELD, *Union Carbide Corporation.*—The influence of a varying electrostatic potential on photoelectric emission from the space charge region of a semiconductor is calculated using Ge as an example. The variation in energy of the valence band edge (as obtained by numerical integration[1]) within a few penetration depths of the light is shown to be significant (~0.1 ev). The expected photocurrent i is then calculated at each depth x, weighted by the light intensity $\exp(-\alpha x)$, and integrated over x between limits which depend on the specific case considered. On using the conventional model for semiconductors,[2] i has been evaluated numerically for intrinsic and doped crystals with bands bent up or down. The results depart appreciably from previously expected behavior near the threshold energy, and an essential asymmetry arises between n- and p-type materials as well as between positive and negative surface charges. For all nonzero space charges, a "tail" is predicted which compares well with the kind normally found at low energies in measurements of photoemission from semiconductors.[2] These conclusions are not strongly dependent on the model cited.

[1] G. C. Dousmanis and R. C. Duncan, Jr., J. Appl. Phys. **29**, 1627 (1958).
[2] L. Apker, E. Taft, and J. Dickey, Phys. Rev. **74**, 1462 (1948).

NA3. Electron Lifetime in p-type InSb. R. W. CUNNINGHAM, *Texas Instruments Inc.*—The photomagnetoelectric effect has been used to obtain information about the lifetime and transport of electrons in p-type InSb at approximately 80°K. The measuring technique is the same as described previously,[1] with the addition of a venetian blind type optical attenuator. Measurements are for material etched to obtain a low surface recombination velocity. The lifetime is strongly dependent on the photon flux and thus on the surface concentration of electrons. The concentration is estimated as 10^{14} m^{-3} for photon fluxes of about 10^{19} m^{-2} sec^{-1}. This concentration is much larger than the equilibrium concentration. Lifetime as a function of concentration increases to a maximum, goes through a minimum, and then rises as the concentration increases. Results for different magnetic fields are similar, but the positions of the maximum and minimum shift. The curves for all fields coincide when properly scaled to fit at the minimum. The amount of adjusting as a function of magnetic field allows an estimate of the electron mobility. The results indicate the collision time is energy dependent.

[1] R. W. Cunningham, Bull. Am. Phys. Soc. **5**, 186 (1960).

NA4. Large Signal Photomagnetoelectric (PME) Effect. ALAN R. BEATTIE, *Texas Instruments Inc.*—A theoretical analysis is given of the steady state PME effect when the usual small signal approximation is violated, that is, when the concentration of nonequilibrium carriers produced by the incident illumination exceeds the equilibrium concentration of minority carriers. The recombination rate of excess minority carriers may not be linear with the concentration of the excess carriers, and a concentration dependent "lifetime," $\tau(\Delta n)$, is defined by $R = \Delta n/\tau(\Delta n)$, where R is the recombination rate and Δn is the concentration of excess minority carriers. Experimental results on p-type InSb at liquid-nitrogen temperature[1] are analyzed on the basis of this theory and the dependence of the "lifetime" on excess carrier concentration is found. The electron and hole relaxation times are energy dependent and an estimate of the zero magnetic field electron mobility is made.

[1] R. W. Cunningham, preceding abstract.

NA5. Infrared Absorption in Magnesium Silicide and Magnesium Germanide.* P. KOENIG,† D. W. LYNCH, AND G. C. DANIELSON, *Iowa State University.*—Infrared absorption spectra of several n-type Mg_2Si and Mg_2Ge single crystals were obtained in the wavelength regions from 1 to 13 μ and 1 to 7 μ, respectively, over the temperature range from 85° to 370°K. Free carrier absorption occurred in Mg_2Si at the longer wavelengths. The absorption edges appeared to be due to indirect transitions and the shifts of the optical energy gaps with temperature are estimated to be -5×10^{-4} ev (K°)$^{-1}$ for Mg_2Si and -6.5×10^{-4} ev (K°)$^{-1}$ for Mg_2Ge. No values for the gaps were determined from the present data, but they can be seen to be approximately equal to the gaps determined by electrical measurements. An absorption peak at 0.40 ev in n-type Mg_2Si was observed and is tentatively ascribed to a transition from a conduction band minimum to a higher conduction band.

* Work was performed in the Ames Laboratory of the U. S. Atomic Energy Commission.
† Present address: 180 Princeton Avenue, Buffalo 26, New York.

NA6. High-Resolution Oscillatory Magneto-Absorption Measurements of InSb at Liquid-Helium Temperature. SOLOMON ZWERDLING AND JOHN P. THERIAULT, *Lincoln Laboratory,** *M.I.T.*—The OMA spectrum of the valence-conduction band transitions in InSb has been measured under high resolution with polarized radiation, using an infrared grating spectrometer, liquid-helium temperature, and an unstrained high-mobility single crystal sample 5 μ thick. The absorption edge occurred between 0.2346 and 0.2382 ev at zero field, and 15 clearly defined transmission minima were observed at energies greater than 0.2360 ev with $E \perp B$ and fields as low as 5.0 kgauss. Upward curvature with increasing field was particularly evident in the shift of the first two minima, as expected for transitions to exciton levels. Interpreting the two

minima as a Zeeman splitting of the lowest zero-field exciton level yields a g factor of 43.5 ± 0.5, somewhat lower than the spin resonance value of Bemski, suggesting complications from the valence band. An additional splitting of the lower component was observed for $E\perp B$, starting just below 20 kgauss, increasing and becoming very pronounced at 38.9 kgauss. Higher-energy minima also split with increasing field above 20 kgauss first into doublets, then quadruplets. The energy gap found was 0.237 ± 0.002 ev as determined from the coalescence of all minima extrapolated smoothly to zero field. Values of the apparent effective mass are consistent with published values.

* Operated with support from the U. S. Army, Navy, and Air Force.

NA7. Exciton Structure and Zeeman Effects in Uniaxial Crystals of Small Anisotropy.* J. O. DIMMOCK AND R. G. WHEELER, *Yale University.*—The presence of an external magnetic field has been included in a Hamiltonian for the exciton system in the effective mass approximation obtained by Dresselhaus.[1] This has been approximated to the case of uniaxial crystals of small anisotropy by the assumption that the effective mass tensor for both the electron and hole is diagonal, the transverse mass components are equal within each tensor, the remaining anisotropy is small, and the anisotropy in the dielectric constant is cylindrical and small. A brief calculation puts the resulting Hamiltonian in a form sufficiently close to that of the Hamiltonian for the hydrogen atom that first order perturbation techniques may be employed to obtain the zero field deviation of the spectrum from hydrogen-like in terms of the mass and dielectric anisotropies. If the components of the dielectric constant are presumed known, the magnetic field perturbations for H parallel and perpendicular to the crystal C axis depend only on the longitudinal and transverse electron and hole masses such that a comparison of this theory with experiment will yield values for the electron and hole mass tensors in the above approximation.

* Supported in part by the Office of Scientific Research, U. S. Air Force.
[1] G. Dresselhaus, J. Phys. Chem. Solids **1**, 15 (1956).

NA8. Exciton Spectra and Zeeman Effects in Cadmium Selenide.* R. G. WHEELER AND J. O. DIMMOCK, *Yale University.*—The exciton spectra of cadmium selenide has been observed and identified by optical reflection, absorption, and Zeeman effects at 1.8°K. The results of the reflection experiments indicates the presence of two nonoverlapping exciton series. From the observed optical selection rules relative to the crystal C axis, the conduction band is identified as having a Γ_7 symmetry. The two series correspond to the $\Gamma_9-\Gamma_7$ valence band splitting of approximately 210 cm^{-1}. The absorption and magnetic effects have identified the $n=1$; $n=2$, p_s, p_{xy}; $n=3$ states of the lowest energy series. By using the analysis of the previous abstract, the following band parameters have been obtained; $E_g=14851$ cm^{-1}; the exciton mass $m_{ex\perp}{}^*=0.11m_e$, $m_{ex\parallel}{}^*=0.14m_e$; the electron mass $m_e{}^*=0.13m_e$; the hole mass $m_h{}^*\sim0.5m_e$. The electron g values are anisotropic with $g_\parallel=|1.65|$ and $g_\perp=|0.45|$. By using a calculation similar to Roth,[1] one estimates that $g_\parallel$ must be negative implying a spin-orbit splitting of the valence band of the order of 5000 cm^{-1}. The effect of the finite photon momentum is observed in the Zeeman splitting of the $n=2$ p states upon 180° rotation of the magnetic field perpendicular to the crystal C axis.

* Supported in part by the Office of Scientific Research, U. S. Air Force.
[1] L. M. Roth, Phys. Rev. **118**, 1534 (1960).

NA9. Absorption Edge of Zinc Telluride. E. LOH AND R. NEWMAN, *Hughes Research Laboratories.*—The absorption and reflection spectra of ZnTe single crystals near the absorption edge have been studied from liquid-helium to room temperature. The temperature and photon energy dependence of the absorption coefficient at the edge are similar to that of CdS.[1] At low temperatures, the reflection spectra show a single sharp maximum-minimum structure. The absorption spectra of some crystals show at least one peak near the absorption edge. Both the reflection and the absorption spectra indicate the existence of exciton states. Damage by mechanical polishing increases the absorption coefficient (or shifts the absorption edge toward longer wavelengths) and destroys the exciton peak at the absorption edge. ZnTe alloyed p-n junctions have been fabricated and some preliminary information on their photovoltaic behavior has been obtained.

[1] D. Dutton, Phys. Rev. **112**, 785 (1958).

NA10. Band-Edge Absorption and Emission Properties of CdTe. R. E. HALSTED, D. T. F. MARPLE, M. LORENZ, AND B. SEGALL, *General Electric Research Laboratory.*—At 20°K the absorption coefficient of CdTe rises from less than 10^3 cm^{-1} at 1.58 ev to about 4×10^4 cm^{-1} at 1.60 ev. A single peak attributed to exciton absorption is observed at 1.594 ± 0.001 ev with $\alpha_{max}\sim8\times10^4$ cm^{-1} and half-width of 0.003 ev. A direct transition is indicated. Exciton and edge emission spectra are observed as two series of doublets with separations of 0.003 and 0.008 ev, respectively. With decreasing temperature the peaks shift less than 10^{-4} ev/°K and the doublet peaks of lower energy become dominant. The highest energy exciton emission peak at 1.5926 ± 0.0005 ev coincides with the absorption peak within present experimental error. The highest energy peak of the edge emission series occurs between 1.53 and 1.56 ev. An edge emission shift to higher energy may be correlated with increasing oxygen concentration. The energy of the impurity band maximum, 1.43 ev, corresponds with emission previously correlated with Cd vacancies.[1] All three patterns exhibit structure attributed to longitudinal optical phonons with $\hbar\omega=0.0213\pm0.0002$ ev. This is consistent with measurements of reststrahlen frequency,[2] static and optical dielectric constants, and compressibility.[1]

[1] D. deNobel, Phillips Research Repts. **14**, 488 (1959).
[2] P. Fisher and H. Fan, Bull. Am. Phys. Soc. **4**, 409 (1959).

NA11. Exciton and Interband Absorption in Silicon Carbide, Polytype 15*R*. LYLE PATRICK, W. J. CHOYKE, AND D. R. HAMILTON, *Westinghouse Research Laboratories.*—Exciton and interband absorption have been reported[1] for two SiC polytypes, namely, 4*H* and 6*H*. We now report similar data for polytype 15*R*, in which the transitions are again indirect (phonon assisted). Two absorption spectra were obtained by using polarized light, with electric vector parallel or perpendicular to the crystal c axis. Three phonon energies can be found by analyzing the data, and the phonons are found to be somewhat different for the two polarization directions of the light. The measurements show that there are significant energy-band differences between the SiC polytypes. These differences will be discussed. Crystallographically, the SiC polytypes differ only in the ordering of the atomic planes which are perpendicular to the c axis.

[1] W. J. Choyke and Lyle Patrick in *Proceedings of 1960 International Conference on Semiconductors (Prague)* (to be published).

WEDNESDAY MORNING AT 9:30

King Hall

(F. REIF presiding)

Invited Papers on Low Temperatures

O1. Self Diffusion and Spin Relaxation in Solid Helium-3. H. S. REICH, *IBM Watson Laboratories.* (30 min.)

O2. Nuclear Resonance and Exchange Forces in Helium-3. J. GOODKIND, *Stanford University.* (30 min.)

O3. Helium-2 in Rotation. G. T. LANE, *Yale University.* (30 min.)

O4. The Effect of Superconductivity on the Elastic Moduli of Cubic Metals. G. A. ALERS, *Ford Motor Scientific Laboratory.* (30 min.)

WEDNESDAY MORNING AT 10:00

Copper Cup Room, Herrmann Hall

(L. I. SCHIFF presiding)

Nuclear Physics

OA1. A Composite Nuclear Model. KEATON KELLER, *University of Arizona.*—The outline of a nuclear model will be discussed which assumes that nucleons are correlated into alpha clusters and at the same time have a shell structure determined by a LS coupling scheme. A type of LS coupling, in which the intrinsic spins of the nucleons within an alpha particle interact with each other, but not with the spins of nucleons outside the alpha particle, is assumed. The total orbital angular momentum is determined by the interaction of all the orbital angular momentum vectors within a shell composed of alpha particles, each with its own value of l. A possible quantum-number scheme showing the so-called magic numbers will be given. The large binding energy of the alpha particle causes the spatial subgrouping of the nucleons. A semi-empirical binding-energy equation in terms of the alpha-particle aspect of this model will be presented. The saturation of binding energy and radioactivity will be discussed using this equation. The possibility of triton clusters in certain light nuclides will be considered. The magnetic moments of Li^7, Be^9, B^{11}, F^{19}, Na^{23}, and Al^{27} will be interpreted using this model.

OA2. Tensor Interaction and Nuclear Matter. BRUCE L. SCOTT, *University of Southern California,* AND S. A. MOSZKOWSKI, *University of California, Los Angeles.*—The separation method of Moszkowski and Scott[1] has been applied to the calculation of the properties of nuclear matter using two different nucleon-nucleon potentials, both in reasonable agreement with two-body data. Calculations with the potential of Brueckner and Gammel gave $E/A=-14.2$ Mev at an equilibrium density corresponding to $k_f=1.5f^{-1}$. The difference from the results of B and G may be caused by slow convergence of the series (especially in the triplet-even state where the tensor interaction has a large 2nd order contribution). An important factor in obtaining nuclear saturation is shown to be the weakening of tensor interaction effects by the Fermi sea. Evidence for this may also be seen from the results obtained using a different two nucleon potential which, however, still gives good fits to two body data. The potential chosen has a much weaker tensor component and shows no sign of saturation at normal densities (at $k_f=1.5f^{-1}$, $E/A=-23.4$ Mev). The difference in the two results appears to be much larger than can be accounted for either by higher order terms or by differences in the phase-shift approximation to the reaction matrix.

[1] S. A. Moszkowski and B. L. Scott, Ann. Phys. 11, 65 (1960).

OA3. Preliminary Results on Neutron Form Factors. R. HOFSTADTER, C. DE VRIES, AND D. W. AITKEN, *Stanford University,* AND R. HERMAN, *General Motors Corporation.*—High-energy inelastic electron scattering experiments were made recently on the deuteron in conjunction with comparison elastic scattering measurements on the proton. In this way absolute values can be assigned to the deuteron peak cross sections at pairs of energies and angles at the same value of the momentum transfer (q). The results have been analyzed in terms of the modified Jankus theory, incorporating Dirac (F_{1N}, F_{1P}) and Pauli (F_{2N}, F_{2P}) from factors of the neutron and proton. The values of F_{1N} and F_{2N} were found by the "method of intersecting ellipses" assuming known values of F_{1P} and F_{2P}. Meson-exchange effects and final-state interactions have been neglected in the analysis. Preliminary results are that $F_{1N}\neq 0$ at large values of q^2, is negative and is approximately -0.40 at $q^2=15f^{-2}$. These preliminary results also indicate that F_{2N} is close to, but lies below F_{2P} and that F_{2N} goes to zero near $q^2\cong 17f^{-2}$. An ambiguity in the signs and values of F_{1N} and F_{2N} will be discussed. Since final state interactions and other corrections have been evaluated only approximately, the results are approximate and should be used only to indicate trends of the neutron form factors. Further work is in progress.

OA4. Nuclear Temperatures from Neutron Bombardment.* RONALD I. EWING, *Sandia Laboratory,* AND T. W. BONNER, *Rice University.*—The energy spectra of neutrons inelastically scattered from W, Ta, Sn, Cd, and Fe under bombardment with neutrons of energies 2.44, 5.0, and 7.0 Mev have been obtained using a new type of neutron spectrometer.[1] The spectra are fit by the "evaporation" distribution, $N(E)\sim E\times\exp(-E/T)$, where T is the nuclear temperature in units of energy. The analysis of the data included corrections for multiple scattering of neutrons in the samples. The table lists the nuclear temperatures ($\pm 10\%$) in Mev for bombarding neutrons of energy E_b in Mev. For $E_b=2.44$ and 5.0 Mev,

E_b	W	Ta	Sn	Cd	Fe
2.44	0.38	0.37	0.52	0.45	
5.0	0.55	0.50	0.64	0.62	0.85
7.0	0.57	0.49	0.77	0.73	0.74

$E_b=aT^2$, with $a(\text{Mev})^{-1}=A/(9\pm 2)$. The nuclear temperatures for Sn and Cd also follow this relation at $E_b=7.0$ Mev.

* Supported by the U. S. Atomic Energy Commission.

[1] Bramblett, Ewing, and Bonner, Nuclear Instruments and Methods 9 (1960).

OA5. $He^3(He^4,\gamma)Be^7$ Reaction at Excitation Energies 8 to 15 Mev.* A. W. FAIRHALL, *University of Washington.*—Targets of He^3 have been bombarded with He^4 ions to give the $He^3(He^4,\gamma)Be^7$ reaction. The yields of Be^7 were determined radiochemically. At excitation energies of the Be^7 compound system of 14.7, 11.0, 9.4, and 7.8 Mev, the formation cross section of Be^7 is 15, 13, 15, and 18 μbarn, respectively. It is very unlikely that the production of Be^7 could be due to any reaction other than fusion of He^3 with He^4. These cross sections are an order of magnitude larger than that which is observed[1] at an excitation energy of 3 Mev. With cross sections of this magnitude, this reaction could be very important astrophysically, Under the conditions of the implosion of a star, very large amounts of Be^7 could be formed, thus lending support to the Be^7 hypothesis for explaining the light curve of type I supernovas.

* Supported in part by the U. S. Atomic Energy Commission.
[1] H. D. Holmgren and R. L. Johnston, Phys. Rev. 113, 1556 (1959).

OA6. Angular Distributions of Specific Fission Fragments in Helium-Ion Induced Fission of Lead.* RICHARD E. WILSON AND A. W. FAIRHALL, *University of Washington.*—The angular distributions of specific fission fragments emitted in the fission of natural lead bombarded with 42-Mev helium ions has been studied radiochemically. Fission into fragments having a mass ratio greater than about 1.23 have an anisotropy, represented by the ratio of the differential cross section at 0° to that at 90° to the beam, of 2.0. For fragments with mass ratio less than 1.23, the anisotropy increases markedly with decreasing mass ratio. This result, along with the measured mass yield curve and fission excitation function of lead,[1] is interpreted to mean that 80% of the fission occurs before a neutron is evaporated, with an angular anisotropy of 2. The remaining 20% of the fission occurs after the evaporation of one neutron, with an anisotropy greater than 8. This second chance fission evidently has a mass distribution which is very narrow, the full width at half-maximum being about 10 mass units.

* Supported in part by the U. S. Atomic Energy Commission.
[1] E. F. Neuzil, Ph.D. thesis, University of Washington, 1959 (unpublished).

OA7. Recoil of Cu Atoms From Cu^{63} (γ,n) Cu^{62} Reactions in Thin Films.* V. A. J. VAN LINT, R. A. SCHMITT, AND C. S. SUFFREDINI, *General Atomic.*†—The absorption of Cu^{62} atoms recoiling from (γ,n) reactions in thin films of copper evaporated onto aluminum has been studied by a sandwich irradiation technique.[1,2] The data represent the dependence of the fraction of the transmitted atoms recoiling out of the film on the film thickness. Theoretically, for a unique range R, the recoil fraction f out of one surface of a film of thickness x is

$$f=1/2(1-x/2R) \quad \text{for} \quad x<R$$
$$=R/4x \quad \text{for} \quad x\geq R.$$

More complicated dependencies result for a distribution of ranges. The experimental results are consistent with a distribution of ranges calculated from the photoneutron spectrum and an assumed proportionality between range and energy for the recoil atoms.[2]

* Sponsored by Air Force Research Division, Air Research and Development Command, U. S. Air Force.
† John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic Division of General Dynamics, San Diego, California.
[1] R. A. Schmitt and R. A. Sharp, Phys. Rev. Letters 1, 445 (1958).
[2] V. A. J. van Lint, R. A. Schmitt, and C. S. Suffredini, Phys. Rev. (to be published).

OA8. Ranges of Recoil Atoms from (γ,p) and (γ,α) Reactions.* R. A. SCHMITT, C. S. SUFFREDINI, AND V. A. J. VAN LINT, *General Atomic.*†—The ranges of atoms recoiling from (γ,p) and (γ,α) reactions have been measured by the same sandwich irradiations technique previously applied to (γ,n) reactions.[1,2] Estimates of the recoil energy were deduced from experimental and theoretical information on photoproton and photoalpha spectra. Slight corrections were performed for the momentum imparted by the incident gamma ray. The results include the following range energy points (E in kev, R in A): Co^{61} in Cu: $E=475$, $R=1600\pm200$; Ag^{111} or Ag^{112} in Cd; $E=81$, $R=190\pm20$; Y^{90} or Y^{93} in Zr: $E=93$, $R=315\pm50$; Sc^{47} in Ti: $E=160$, $R=640\pm50$; Co^{61} in Ni: $E=130$, $R=280\pm20$.

* Sponsored by Air Force Research Division, Air Research and Development Command, U. S. Air Force.
† John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic Division of General Dynamics, San Diego, Calif
[1] R. A. Schmitt and R. A. Sharp, Phys. Rev. Letters 1, 445 (1958).
[2] V. A. J. van Lint, R. A. Schmitt, and C. S. Suffredini, Phys. Rev. (to be published).

OA9. Effect of Surface on Fission Fragment Trajectories.* W. G. BRAMMER AND J. A. BRINKMAN, *Atomics International.*—Electron microscope examinations[1] of fission tracks in thin films have shown a deviation from the expected distribution in the number of long path lengths observed. This has been explained by the scattering of fission fragments out of the film. When an external source of fission fragments was used, the discrepancy occurred at still smaller path lengths. The effect on the fission fragment trajectories of material surfaces through which they pass is considered here. Refraction of fission fragments at the surfaces may account for some of these discrepancies. An index of refraction, and correspondingly, a most probable angle of deviation may be calculated for any material.[2] The frequency of occurrence of the longer path lengths is predicted to be smaller if the fission fragments originate outside a thin film than if they occur within the film. Results of numerical calculations will be presented.

* This work supported by the U. S. Atomic Energy Commission.
[1] T. S. Noggle and J. O. Stiegler, J. Appl. Phys. 31, 2199 (1960).
[2] F. K. Richtmeyer and E. H. Kennard, *Introduction to Modern Physics* (McGraw-Hill Book Company, Inc., New York, 1947), p. 239.

OA10. Delayed Particles in Extensive Air Showers.* P. J. ECCLES,† *Melbourne University.*—Over two million showers have been analyzed by two 5-m horizontally separated liquid scintillators and associated electronics to obtain 2200 showers with delayed particles in the range 0.2 to 1.8 μsec with respect to the shower "front." Their delay distribution fits an exponential of mean delay 0.124 μsec. These particles are identified as μ mesons, from the mean delay of their decay electrons observed in the deeper (35 cm) scintillator, and do not include mucleons, but may include electrons. They are delayed by a mechanism other than velocity differences between themselves and the shower front. They seem distributed as the μ-meson component in showers, and their apparent population in showers (0.7%) leads to 2.5% as their real population, assuming their distribution is the μ-meson lateral distribution. It is likely that their heights of origin are similar to those of the normal μ component. In the range 100–250 Mev, their energy spectrum is measured as $N(>E)\propto E^{-0.37}$. Methods of production and delay are discussed. The delayed particles are accompanied by nucleus with a mean delay of 0.7 μsec with respect to the shower "front."

* Supported by a General Motors-Holdens Research Fellowship.
† Present address: M.I.T. Volcano Ranch Air Shower Project.

OA11. Strata Effect in Scintillation Spectrometry. IRVING BOEKELHEIDE, *Chico State College.*—A Cs^{137} "point" source beam was collimated by a $\frac{1}{4}$-in. straight hole through a 2-in. block of lead, then impinged upon a 3×3 in. NaI(Tl) crystal along a diameter at five selected strata positions. These strata positions were evenly spaced at intervals along the axis of the crystal. To minimize the effect of drift in electronics, four differential pulse-height data runs were taken back and

forth through each of the five positions. As described elsewhere,[1] the position of the photopeak was carefully determined by finding the Gaussian distribution that was most nearly represented by the data. The results show a well-defined trend toward an appearingly less energetic photopeak when the interaction occurs in a strata close to the face of the phototube. These results are consistent with the work of Peelle and Love[2] who report on the displacement of the "sum peak."

[1] Irving Boekelheide, Rev. Sci. Instr. 31, 1001 (1960).
[2] R. W. Peele and T. A. Love, Rev. Sci. Instr. 31, 205 (1960).

WEDNESDAY MORNING AT 9:30

Terrace Room, Mark Thomas Inn

(J. PLATT presiding)

Chemical Physics I

P1. Theory of Electron Spin Resonance of Free Radicals in Solution.* JAMES D. CURRIN, *Stanford University* (introduced by L. I. Schiff).—The electron spin resonance spectrum of the free radical 1,3-bisdiphenylene 2-phenyl allyl exhibits, in solution, a hyperfine structure due to the coupling of an unpaired electron with eight equivalent protons. Hausser[1] has found that the resolution, proceeding from a temperature at which the lines are well separated, becomes progressively poorer as the temperature is increased, until the hyperfine structure disappears altogether. The total width of the spectrum remains constant throughout. A calculation of the spectrum has been made under the assumption of random flipping of the proton spins, as in the random frequency modulation theory of Anderson and Weiss.[2] The computed spectra for increasing values of the proton spin flip rate agree quite well with those obtained by Hausser for increasing temperatures. Ordinary mechanisms of nuclear spin relaxation in solutions of paramagnetic ions do not, however, appear to provide relaxation times short enough to account for the effect.

* Supported in part by the U. S. Air Force through the Air Force Office of Scientific Research.
[1] K. H. Hausser, Z. Naturforsch. 14a, 425 (1959).
[2] P. W. Anderson, J. Phys. Soc. Japan 9, 888 (1954).

P2. Electron Spin Resonance Study of Nitro-Group-Alkali Metal Interactions in Aromatic Hydrocarbons.* RAYMOND L. WARD, *Lawrence Radiation Laboratory, Livermore.*—The reaction of an alkali metal with nitrobenzene, *o*-dinitrobenzene, *m*-dinitrobenzene, *p*-dinitrobenzene, sym-trinitrobenzene, nitromesitylene, dinitromesitylene, and trinitromesitylene in 1,2-dimethoxyethane has been carried out, and the resulting paramagnetic solutions studied using electron spin resonance techniques. The nitrogen hyperfine coupling constants have been determined for each molecule, while proton coupling constants have been determined in a few cases. All polynitro compounds studied, except *o*-dinitrobenzene, possess only *one* nitrogen hyperfine interaction. This is in contrast to the results obtained in the electrolytic preparation of free radicals,[1] where two equal nitrogen coupling constants are found for each of the isomeric dinitrobenzenes. A comparison of the resulting hyperfine structure of the electrolytically and chemically produced free radicals is presented, and a strong ion-pair theory proposed for the differences obtained.

* This work was performed under the auspices of the U. S. Atomic Energy Commission.
[1] A. H. Maki and D. H. Geske, J. Chem. Phys. 33, 825 (1960).

P3. ESR Spectrum of Formyl Radical at 4.2°K.* EDWARD L. COCHRAN, *Johns Hopkins University.*—The electron spin resonance spectrum of formyl (HCO) radical has been observed in solid argon and in solid carbon monoxide at 4.2°K. In argon the radical was prepared by photolysis of methanol using a hydrogen discharge lamp with a sapphire window. In carbon monoxide the radical was prepared by the reaction of hydrogen atoms with the matrix.[1] The hydrogen atoms were produced *in situ* by photolysis of HI at 2537 A. The reaction, $H+CO \rightarrow HCO$, is quantitative, i.e., no free H atoms were observed. The spectrum for HCO is a doublet with a separation between lines of 134.5 gauss at 9171 Mc. The lines are asymmetrical due apparently to *g*-factor anisotropy. The width between points of maximum slope is 10.9 gauss for the low-field line, and 20.7 gauss for the high-field line. This difference in width could arise from the combination of an anisotropic hyperfine interaction with the *g*-factor anisotropy.

* Work supported by Bureau of Naval Weapons, Department of the Navy.
[1] G. E. Ewing, W. E. Thompson, and G. C. Pimentel, J. Chem. Phys. 32 927 (1960).

P4. Observation of Electron Spin Resonance at $g=4$ in Crystalline Organic Radicals.* J. H. BURGESS AND R. S. RHODES, *Stanford University.*—We have observed a transition at $g=4$ at low temperatures and low frequencies in the ESR spectrum of each of the free radicals picryl-*n*-amino-carbazyl, 1,3-bisdiphenylene-2-phenyl allyl and Wurster's blue. In a frequency range from 20 to 200 Mc/sec the *g* value is 4 within 3% and is independent of temperature. However, at a fixed frequency the intensity of the absorption decreases at higher temperatures and vanishes above a temperature T^* characteristic of the particular free radical. Because of antiferromagnetic exchange coupling, the static susceptibility of the free radicals exhibits a maximum as a function of temperature. In all cases T^* falls below the temperature of this maximum indicating that "exchange motion" is effective in averaging out the interactions responsible for the $g=4$ transition. At fixed temperature the resonance decreases in intensity at higher frequencies and has not been observed above 200 Mc/sec. In all three substances there is an indication of an unresolved resonance at $g=6$. Since the dipolar interaction between electron spins is of the order of 200 Mc/sec these resonances may be related to the satellite lines discussed by Van Vleck.[1]

* Supported by the U. S. Air Force Office of Scientific Research.
[1] J. H. Van Vleck, Phys. Rev. 74, 1168 (1948).

P5. Matrix Effect on the ESR Spectrum of Trapped Nitrogen Atoms.* FRANK J. ADRIAN, *The Johns Hopkins University.*—ESR studies of trapped nitrogen atoms show that the matrix interaction increases the hyperfine splitting A by some 10 to 20% of the free atom value of 10.45 Mc/sec. This effect can be accounted for by Van der Waals interactions between the trapped atom and the matrix. These interactions introduce $(2s)(2p)^4$ excited states into the nitrogen wave function. Since the $2p$ shell of the ^4S nitrogen atom already contains three electrons with the same spin, only that $2s$ electron with the opposite spin can be excited. This creates a positive unpaired electron density at the nucleus. Perturbation theory gives the following results. If we assume eight nearest

neighbors, the experimental value of A in argon (12.6 Mc/sec)[1] corresponds to a nearest-neighbor distance of 7.5 a_0. The value of A observed in neon (11.45 Mc/sec)[2] corresponds to a nearest-neighbor distance of 6.8a_0. These separations are close to the values for an atom trapped substitutionally without lattice distortion.

* Work supported by Bureau of Naval Weapons, Department of the Navy.
[1] E. L. Cochran (unpublished results).

P6. Multiple Proton Magnetic Relaxation Times in Liquids. J. G. POWLES, *Queen Mary College, London.*—Measurements will be reported of the proton spin lattice relaxation times at 47.5 Mc/sec in liquid toluene, ethyl benzene, bromobenzene, chlorobenzene, fluorobenzene, henzene, aniline, paraxylene, mesitylene, and methyl alcohol. The T_1 values have been measured by saturation and recovery of the proton signals under moderately high resolution. Where more than one type of chemically shifted proton is present, both relax independently with different T_1's which have a different dependence on temperature. For example, the ring proton in toluene has a minimum in the liquid but the methyl proton does not. The multiple T_1's for each liquid will be interpreted in terms of complex reorientational and internal motions of the molecules in the liquid.

P7. Long-Range Proton Spin Coupling. Nuclear Magnetic Resonance of CH_3CCCH_2OH.* VICTOR W. LAURIE, *Stanford University.*—A study of the nuclear magnetic resonance spectrum of 2-butyne-1-ol (CH_3CCCH_2OH) has been made. A preliminary value of 2.3 cps for the methyl-methylene proton spin coupling has been obtained. This coupling is between protons separated by five bonds and shows the strong effect of the triple bond. The chemical shift of the methyl group relative to the methylene group is 2.3 ppm. Effects of hydrogen bonding on the OH resonance will be discussed.

* Supported in part by the National Science Foundation.

P8. Spin Hamiltonian Anisotropies for a Dibridged Bis-Cobalt Ion.* JOHN A. WEIL AND GORDON L. GOODMAN, *Argonne National Laboratory.*—Solutions containing $M=[en_2Co(O_2,NH_2)Coen_2]^{4+}$, *en* denoting ethylenediamine, give EPR indicating an unpaired hole S interacting, on the average, equally with the nuclear spin, $I^{(i)}=\frac{7}{2}$, of each cobalt ($i=1,2$).[1] At 300°K, X-band EPR of M diluted in single crystals of $[en_2Co(NO_2,NH_2)Coen_2](NO_3)_4$ reveals anisotropies of $\kappa=\beta\mathbf{S}\cdot\mathbf{g}\cdot\mathbf{B}+\Sigma_i\mathbf{S}\cdot\mathbf{A}^{(i)}\cdot\mathbf{I}^{(i)}$; $S=\frac{1}{2}$.[1] Striking agreement is seen between the semiresolved spectra observed for various orientations of **B** and patterns computed by GEORGE from superpositions of Gaussian curves located according to κ, using the following eigenvalues and tentative eigenvectors in a molecular basis ($\mathbf{x}$ || Co-Co, $\mathbf{y}\perp$Co-Co and intersecting the bridging N, $\mathbf{z}$): $\mathbf{g}$(**2.079**: −0.94, −0.02, −0.35; **2.023**: +0.11, −0.96, −0.24; **2.010**: −0.34, −0.26, +0.91); $\mathbf{A}^{(1)}$ (±**30.1** gauss: −0.67, +0.74, −0.04; ±**8.5**: +0.45, +0.45, +0.77; ±**1.1**: −0.59, −0.50, +0.63); $\mathbf{A}^{(2)}$ (±**30.1**: +0.78, +0.63, +0.11; ±**8.5**: −0.36, +0.59, −0.72; ±**1.1**: +0.51, −0.52, −0.68). Four sites for M per unit cell of this monoclinic crystal ($P2_1/m$) complicate projections of molecular quantities onto the crystallographic axes: **a**, **b** (twofold axis), **c** (needle axis); $\beta_{ac}=94°$.[2] With Cartesian axes (**a'**,**b**,**c**), $\mathbf{g}$ is (**2.079**: +0.57, +0.72, −0.39; **2.023**: −0.82, +0.54, −0.18; **2.010**: +0.08, +0.43, +0.90) for one site.

* Work under auspices of U. S. Atomic Energy Commission.
[1] E. A. V. Ebsworth and J. A. Weil, J. Phys. Chem. 63, 1890 (1959).
[2] P. Goldstein and R. Jacobson (private communication).

P9. Microwave Spectrum and Molecular Structure of Sulfur Tetrafluoride. WILLIAM D. GWINN AND WILLIAM M. TOLLES, *University of California, Berkeley.*—The microwave spectrum of SF_4 has been resolved for the S^{32} and S^{34} species. From the moments of inertia a structure is obtained which confirms the conclusion obtained from the NMR spectra[1] which indicates that there are two inequivalent pairs of fluorines. The microwave data show that the molecule has C_{2v} symmetry. The distances between the fluorines in each pair are determined and found to be 1.197 A and 1.643 A. The sulfur is found to be 0.37 A from the center of mass. This leads to bond angles of 185° and 100° with bond distances for each pair of 1.64 A and 1.54 A, respectively. The dipole moment as determined from the Stark effect is 0.64 debye. This structure is in contrast to that of SeF_4 which appears to have D_{2d} symmetry.[2]

[1] F. A. Cotton, J. W. George, and J. S. Waugh, J. Chem. Phys. 28, 994 (1958).
[2] H. J. M. Bowen, Nature 172, 171 (1953).

P10. Bent Carbon-Chlorine Bonds and the Chlorine Nuclear Quadrupole Coupling Constants in 1,1 Dichlorocyclopropane. WILLIS H. FLYGARE, A. NARATH, AND WILLIAM D. GWINN, *University of California, Berkeley.*—The existence of bent C–Cl bonds can be either confirmed or disproved by a determination of the orientation of the principal axes of the chlorine nuclear quadrupole tensor. The deviation of the axis system from the line connecting the carbon and chlorine nuclei should be a measure of the bending in the bond. In an asymmetric rotor such as 1,1 dichlorocyclopropane, microwave spectroscopy leads to an evaluation of only the diagonal elements (χ_{aa}, χ_{bb}, and χ_{cc}) of the quadrupole coupling tensor where a, b, c refer to the inertial axes. It was possible to determine χ_{ab} by measuring the diagonal elements in the Cl^{35}–Cl^{36} isotopic species, followed by a measurement in the Cl^{35}–Cl^{37} species in which the inertial axes are rotated. These measurements demanded extremely high accuracy for weak lines and required the development of a phase stable lock-in system for the klystron frequency drive. The resulting quadrupole constants for Cl^{35} were found to be $\chi_{aa}=-43.545$, $\chi_{bb}=4.100$, and $\chi_{cc}=39.445$, all ±0.005 Mc. On using the Cl^{35}–Cl^{37} data, the principal coupling constants were found to be $\chi_1=-76.4$ ±0.3, $\chi_2=37.0\pm0.3$, and $\chi_3=39.445\pm0.005$ Mc. The angle between the principal axes and the C–Cl internuclear line is 0±15′. This is strong evidence against bent C–Cl bonds in 1,1 dichlorocyclopropane.

P11. Vibrational Relaxation Time for Carbon Monoxide at Room Temperature.* W. E. WOODMANSEE AND J. C. DECIUS, *Oregon State College.*—A spectrophonic method has been developed to measure the rate at which vibrational energy, excited by modulated infrared irradiation, is transformed into translational energy in a gas. The present experiment utilizes frequency response in the audio range, unlike the small phase-shift methods which have been described earlier. Although the result is complicated by acoustic cell resonances, the relaxation loss in CO at room temperature seems to be reasonably well described by a factor of the form $(1+\omega^2\tau^2)^{\frac{1}{2}}$ with $\tau=2\times10^{-8}/p$, where τ is in seconds and p in atmospheres. This result appears to lie fairly close to a linear extrapolation (of a form suggested by theory[1]) of data reported at much higher temperatures for CO, and for the similar molecule N_2.

* This research was supported by the Office of Naval Research.
[1] K. F. Herzfeld and T. A. Litowitz, *Absorption and Dispersion of Ultrasonic Waves* (Academic Press, Inc., New York, 1959), p. 300.

P12. Reactive Scattering in Crossed Molecular Beams. Rubidium Atoms with Methyl Iodide.* JAMES L. KINSEY,† GEORGE H. KWEI, AND DUDLEY R. HERSCHBACH, *University of California, Berkeley.*—The reaction $Rb+CH_3I\rightarrow CH_3+RbI$ has been studied by measurement of the angular distribution of RbI scattered from beams of Rb atoms and CH_3I molecules crossed at right angles. The RbI appears in a broad peak centered at about 65° from the parent Rb beam. Measure-

ments of the total amount of reactive scattering at several temperatures of the incident beams indicate that the activation energy for the reaction is negligibly small. Analysis of the data on the basis of conservation laws for energy and linear momentum shows the qualitative features are similar to those previously found[1] for the reaction of K with CH_3I: strongly anisotropic scattering as seen in the center of mass coordinate system and a concentration of the RbI recoiling backwards with respect to the incoming Rb beam. About 65% of the 25 kcal/mole energy of reaction goes into vibrational and rotational excitation of the products.

* Supported by the U. S. Atomic Energy Commission and the Alfred P. Sloan Foundation.
† Fellow of the Miller Institute for Basic Research in Science.
[1] G. H. Kwei, J. A. Norris, and D. R. Herschbach, Bull. Am. Phys. Soc. 5, 503 (1960).

P13. Mass Spectrum of Isotopic Nitrous Oxides.* G. M. BEGUN AND L. LANDAU, *Oak Ridge National Laboratory* (introduced by C. E. Melton).—The mass spectra of the four species $N^{14}N^{14}O$, $N^{14}N^{15}O$, $N^{15}N^{14}O$, and $N^{15}N^{15}O$ have been recorded. The $(NO)^+$ fragment produced was found to be formed by rearrangment as well as by loss of the end nitrogen. Seven possible ionizing reactions have been proposed which account for the observed mass spectra. The mass spectrum of each of the nitrous oxides contained ions corresponding to metastable transitions. These ions were shown to arise from both spontaneous and collision induced dissociation of the parent molecule ion $(N_2O)^+$. The electron impact dissociation of nitrous oxide will be discussed.

* This paper is based on work performed for the U. S. Atomic Energy Commission by Union Carbide Corporation.

WEDNESDAY AFTERNOON AT 2:00

421 Spanagel Hall

(M. L. HUGGINS presiding)

High-Polymer Physics IV

PA1. Effects of Noncrystallizable Components on the Kinetics of Polymer Crystallization. L. MANDELKERN AND F. GORNICK, *National Bureau of Standards.*—The presence of of either an added noncrystallizable component or one contained within the chains of an undercooled polymeric system results in a continuous variation of the composition of the melt during its crystallization. If, concomitant with this variation, there is a corresponding decrease in the equilibrium melting point of the system, then it can be shown that the isothermal steady state nucleation rate will also decrease with increasing degree of crystallinity. The latter effect originates in an increase in the free energy required for the formation of critical size nuclei and is distinct from effects arising from mutual impingement of growing centers or possible changes in growth habit. Starting with the above considerations, we have been able to show that the attenuation of the calculated nucleation rate increases rapidly with increasing concentration of the noncrystallizable component and that the effect is increasingly pronounced with decreasing initial undercoolings and is sensitive to small amounts of co-ingredient. This analysis is shown to be consistent with available experimental data.

PA2. Sequence Selection Problem in the Kinetics of Bulk Polymer Crystallization. F. GORNICK AND L. MANDELKERN, *National Bureau of Standards.*—In contrast with the purely compositional effects discussed in the preceding paper, we now consider explicitly the chain-like character of the melt and of what we here assume to be a fundamental structural feature of polymer crystallites, namely, that the sequences of contiguous chain units which comprise them are (1) much shorter than the contour lengths of the uncrystallized chains and (2) that the selection of these sequences is a random process resulting in the subdivision of the melt into uncrystallized sequences bounded by crystallites or chain ends. The melt is thus characterized by the distribution of its component sequence lengths, the latter being a function of the degree of crystallinity and the length of the crystallites.[1] By utilizing concepts developed by Flory[2] to account for the equilibrium crystallization of copolymers, we have been able to assess the effect of the decreasing availability of sequences of critical length on the free energy of critical nucleus formation.

[1] J. L. Jackson and F. Gornick (to be published).
[2] P. J. Flory, Trans. Faraday Soc. 51, 848 (1955).

PA3. Microstructure and Growth Mechanisms in Spherulitic Crystallization. F. J. PADDEN, JR.,* AND H. D. KEITH,* *American Viscose Corporation.*—A study of spherulite morphology has been undertaken with two main objectives: (a) to test the validity of the twisted crystalline ribbon model for spherulites exhibiting ringed extinction patterns under the polarizing microscope by direct examination of their microstructure, and (b) to obtain evidence relating to the possibility of systematic segregation of crystalline and amorphous material in the solidification process. In support of the twisted ribbon model, it has been found by electron microscopy that spherulites showing ringed patterns are composed of radial arrays of lamellar fibers which twist cooperatively. The cooperativeness of the twist arises from mutual constraints on the packing of fibers of asymmetrical cross section. Evidence has also been found to support the view that spherulites in both polymeric and nonpolymeric materials are formed through the growth of discrete crystalline fibers followed by solidification of less ordered interstitial regions.

* Present address: Bell Telephone Laboratories, Inc., Murray Hill, New Jersey.

PA4. Interpretation of Melt Crystallization in High Polymers and Related Systems. H. D. KEITH* AND F. J. PADDEN, JR.,* *American Viscose Corporation.*—Most of the features of spherulitic crystallization in high polymers, apart from those related specifically to their macromolecular character, are duplicated by a wide variety of nonpolymeric organic and inorganic systems. This includes the cooperative twisting of orientation which gives rise to distinctive ringed spherulites in both polymeric and nonpolymeric substances. Comparative studies of these lead to an interpretation of spherulitic crystallization in general which would account qualitatively, and on a unified basis, for the principal experimental observations. It does not resort to specific characteristics of any given molecular species and explains general variations of morphology with crystallization temperature and, in polymers, with degree of degradation. The interpretation emphasizes the vital role played in high polymers by polydispersity and the presence of structurally imperfect or severely entangled molecules in the melt upon the course of crystallization and the establishment of twisting orientation.

* Present address: Bell Telephone Laboratories, Inc., Murray Hill, New Jersey.

PA5. Isothermal Crystallization Kinetics of Polyethylene. III. Influence of the Sample Preparation. J. RABESIAKA AND A. J. KOVACS, *Centre de Recherches sur les Macromolecules, Strasbourg.*—Isothermal crystallization in bulk has been compared dilatometrically for linear polyethylene samples which have been molded in different ways including sintering of precipitated powders from dilute solutions. These experiments show significant differences in the crystallization process, which cannot be removed even by prolonged heating of the melt at 180°C prior to crystallization. The data have been analyzed by a new kinetic expression in terms of nucleation and growth processes, and compared to the theoretical approach of Avrami.

PA6. Effect of Hydrostatic Pressure on the Crystallization Kinetics of Natural Rubber. G. M. MARTIN AND L. MANDELKERN, *National Bureau of Standards.*—The crystallization kinetics of purified natural rubber were investigated over the temperature interval +5° to −30°C and pressures up to 600 kg/cm². Avrami type, superimposeable isotherms were observed at all temperatures and pressures. The temperature at which the crystallization rate is greatest increases with increasing pressure while the maximum rate decreases slightly. For temperatures which exceed the maximum the crystallization rate increases with increasing pressure while the converse effect is observed at lower temperatures. These results can be interpreted by considering the competition between the contribution of the thermodynamic and transport terms to the nucleation rate. Increasing hydrostatic pressure will raise the equlibrium melting temperature of the polymer, so that at fixed temperature the undercooling will increase. Concurrently, the magnitude of the transport term will also be increased. At the higher temperatures the contribution of the undercooling should dominate in accord with the observed enhancement of the rate. At the lower temperatures, where the transport terms dominate, the expected decrease in rate is observed.

PA7. Rate of Recrystallization of Polyethylene Single Crystals. W. O. STATTON, *E. I. du Pont de Nemours and Company, Inc.*—Platelet crystals of linear polyethylene recrystallize extremely rapidly when immersed in a bath of a hot liquid such as ethylene glycol, glycerine, or Woods metal. This recrystallization rate is much faster than when heated in air. Heating in the liquids at 127°C causes a 50% increase in the length of the chains between folds to occur in one second; the ultimate increase of 200% occurs in about 10 sec. No definite explanation is apparent at this time for this much faster rate in liquids than in air, although the data suggest that the recrystallization in liquids is a two-step process which has a very fast initial change and a much slower final adjustment; this fast, initial step may not occur in air.

PA8. Specific Heat of Linear and Branched Polyethylene. ELIO PASSAGLIA AND HAGOP K. KEVORKIAN, *American Viscose Corporation.*—The specific heat of linear and branched polyethylene has been measured from 80°K through the melting point. None of the existing theories of the absolute value of the specific heat is adequate over a wide temperature range. If adjusted to fit at intermediate temperatures, both the one-dimensional Debye model and the more extended Stockmayer-Hecht theory give results which are low at both high and low temperatures. The interacting-chain theory of Tarassov fits only at low temperatures. With the data of Sochava it is possible to estimate the absolute entropy of the two materials in the melt. At 415°K these are 9.84±0.05 and 9.18±0.3 eu/mole for linear and branched polyethylene, respectively. If, in spite of no discernible glass transition, we assume that the two-phase picture of polymer structure holds for these materials and that their entropies in the melt are equal, we calculate an entropy of 2.22±1.2 eu/mole for pure polyethylene glass at absolute zero.

PA9. Infrared Spectrum of Poly (Ring-d_5 Styrene) and Assignment of Crystallinity Bands in the Spectrum of Polystyrene. S. KRIMM AND T. ONISHI, *University of Michigan.*—An isotactic ring deuterated polystyrene has been prepared with a Ziegler type catalyst. Its x-ray diffraction pattern exhibits a fiber-axis identity period of 6.65 A, indicating a structure similar to that of isotactic polystyrene. Infrared spectra of the polymer, and its atactic counterpart, were obtained in the region of 4000 to 200 cm^{-1}, polarized spectra in the region of 4000 to 400 cm^{-1}. Many of the spectral changes which occur upon crystallization parallel those in isotactic polystyrene. Characteristic bands at 1365 (σ), 1320 (σ), 1293 (π), and 1191 (π) cm^{-1} increase in intensity upon crystallization, and serve to confirm previous assignments of these bands to CH, CH_2, and skeletal modes. The characteristic splitting of a band at 1050 cm^{-1} in poly (ring-d_5 styrene) into components at 1061 (σ) and 1037 (σ) cm^{-1} parallels the splitting of the 1070 cm^{-1} band in polystyrene, and may suggest a completely skeletal origin of this mode. The assignment of the 542 cm^{-1} band of polystyrene is confirmed by its appearance at 486 cm^{-1} in amorphous poly (ring-d_5 styrene), together with its shift and splitting when the polymer is crystallized. Several other confirmed band assignments help to indicate how changes in conformation and configuration affect the infrared spectrum of polystyrene.

WEDNESDAY AFTERNOON AT 2:00

421 Spanagel Hall

(R. HOFSTADTER presiding)

Nuclear Physics

Invited Papers

Q1. Analogies Between Nuclear and Solid State Structure. L. WILETS, *University of Washington.* (30 min.)

Q2. Recent Developments in Nuclear Instrumentation and Detection. C. E. WIEGAND, *Lawrence Radiation Laboratory.* (30 min.)

Q3. Strong Interactions Among Elementary Particles. J. D. WALECKA, *Stanford University.* (30 min.)

Q4. Recent Directions in Studies of Nuclear Reactions. J. S. BLAIR, *University of Washington.* (30 min.)

WEDNESDAY AFTERNOON AT 2:00

Criscuolo Hall

(P. H. MILLER, JR. presiding)

Degenerate Semiconductors and Impurities

Invited Paper

QA1. Band Structure of Heavily Doped Germanium. H. SCHLOSSER, *General Telephone and Electronics, Bayside, New York.* (30 min.)

Contributed Papers

QA2. Study of the Fermi Level in Degenerate Semiconductors. Y. F. CHANG AND J. J. CHANG, *Purdue University.*—The location of the Fermi level in the energy-band scheme for degenerate semiconductors has been calculated as a function of the concentration of impurity atoms. A metallic-hydrogen model was used to represent the impurity atoms immersed in the host semiconductor. In order to find the edges of the allowed energy bands due to the impurities, the Schrödinger equation governing the motion of the electron in metallic hydrogen was solved by using the cellular method of Wigner and Seitz. Calculations of the confluent-hypergeometric function solutions were done by numerical methods. The band edges for the $1s$, $2p$, and $2s$ impurity bands have been calculated for the entire range of impurity concentrations. A symmetrical-parabolic density of states was assumed for the impurity band, where the effective mass was obtained from kp perturbation calculations. Both general and simplified expressions for the determination of the Fermi level in degenerate semiconductors have been derived. Comparison of the calculated depths of the Fermi levels in degenerate germanium at 300°K against those estimated from tunnel diode characteristics showed very good agreement.

QA3. Optical Absorption Edge of Very Impure Germanium. J. I. PANKOVE, *RCA Laboratories, Princeton.*—Early theoretical treatments of the influence of donor impurities on the band structure of semiconductors have predicted a shift of the conduction band to a lower energy. This effect is in addition to the formation of a tail of density of states. The position of the conduction band edge can be measured directly by means of optical absorption. However, in a degenerate semiconductor, states near the band edge are occupied, thus forbidding the corresponding transitions and displacing the absorption threshold to a higher energy. The absorption of arsenic doped germanium (in the range 5×10^{18} to 6.2×10^{19} cm^{-3}) was measured at room temperature with an accuracy of about 1 cm^{-1} and a resolution of 0.0015 ev. The free carrier absorption, extrapolated to the range of across-the-gap transitions, was subtracted from the measured absorption coefficient. An approximate solution of the energy dependence of the absorption coefficient for the case of a degenerate parabolic band allows a Macfarlane-Roberts type of interpretation. The most striking effect is a shift of the whole conduction band by several hundreths of an electron volt closer to the edge of the valence band. The filling of the band by the Fermi sea is also evident.

QA4. Electrical and Optical Properties of Heavily Doped Germanium. W. G. SPITZER, F. A. TRUMBORE, AND R. A. LOGAN, *Bell Telephone Laboratories, Inc.*—Some room temperature electrical and optical measurements have been made on heavily doped germanium containing arsenic, phosphorus, and antimony impurities. Carrier concentration N vs resistivity ρ plots show the mobility to be a function of the type of donor with $\mu_{As}<\mu_P<\mu_{Sb}$ for any N within $6\times10^{18}\leq N\leq8\times10^{19}$ cm^{-3}. For the same range of N as above, electron effective mass m^* values deduced from infrared reflectivity measurements showed at most only a small increase ($\leq20\%$) with N. Within the experimental accuracy ($\pm10\%$) no difference in m^* was observed between the three donors. However, the free carrier absorption is dependent on the type of donor with $\alpha_{As}>\alpha_P>\alpha_{Sb}$ for a given N and wave number $\bar{\nu}$. Classical theory gives a reasonable correlation between the electrical and optical data if the dispersion due to the free carriers is taken into account and a nearly constant m^* is used.

QA5. Thermoelectric Properties of Heavily Doped *N*-Germanium. R. WOLFE AND R. L. MOORE, *Bell Telephone Laboratories, Inc.*—The Seebeck coefficient S has been measured near room temperature on a number of germanium specimens heavily doped with As, Sb, and P. The electron densities N, determined from Hall effect measurements, were between 6×10^{17} and 5×10^{19} cm^{-3}. The value of S for a given N is essentially independent of the particular dopant, which indicates that the scattering mechanisms and the effective mass of the electrons are also independent of dopant. There is no indication of a large increase in the effective mass at the higher doping levels.[1] Since the resistivity ρ for a given N does depend on the dopant (see previous abstract), the quantity S^2/ρ, which is proportional to the thermoelectric "figure of merit," also varies with dopant. The maximum value of S^2/ρ varies from 5×10^{-4} w cm(°C)^2 for As-doped Ge to 7×10^{-4} for Sb-doped Ge (cf. 4×10^{-4} for Bi_2Te_3). S^2/ρ reaches this maximum when the Fermi level is close to the conduction band edge and $S=-330\mu$ v/°C (cf. -200μ v/°C for Bi_2Te_3). Although the electron mobility is lower in Ge than in Bi_2Te_3 at these doping levels, the maximum S^2/ρ is larger and it occurs at a higher value of S due to impurity scattering.

[1] M. Cardona, W. Paul, and H. Brooks, Helv. Phys. Acta. 33, 329 (1960).

QA6. Nonquadratic Conduction Band in HgSe. GEORGE B. WRIGHT, ALAN J. STRAUSS, AND THEODORE C. HARMAN, *Lincoln Laboratory,* M.I.T.*—Measurements of the electronic plasma reflection minimum as a function of carrier concentration in HgSe show that $m^*/m=1.11\times10^{-22}N\lambda_{min}^2/(\kappa'-1)$ is not constant. With the assumption of sharp degeneracy, and a band model similar to InSb,[1] it can be shown[2] that $[cN\lambda_{min}/1-cN\lambda_{min}^2]^2=32.5\times10^{-22}E_g^2/P^4+8.27\times10^{-20}N^2/P^2$, where $c=1.11\times10^{-22}/(\kappa'-1)$ cm^3/μ^2, E_g is the direct energy gap in ev, and P is a matrix component[1] in ev cm. Sensitivity of the sample surface to polishing and etching made determination of κ' from reflectivity measurements uncertain. The effective mass determined by the splitting of the plasma edge in a magnetic field[3] gave an independent determination of $\kappa'=13$. With this information, a fit of the data to the theoretical model gave $P=9\times10^{-8}$ ev cm, and $E_g\sim0.2$ ev.

* Operated with support from the U. S. Army, Navy, and Air Force.

[1] E. O. Kane, J. Phys. Chem. Solids 1, 249 (1957).

[2] G. B. Wright, thesis (unpublished).

[3] B. Lax and G. B. Wright, Phys. Rev. Letters 4, 16 (1960).

QA7. Electrical Properties of HgSe and HgSe-HgTe Alloys. ALAN J. STRAUSS AND THEODORE C. HARMAN, *Lincoln Laboratory,** *M.I.T.*—The electrical conductivity (σ) and Hall coefficient (R_H) of doped and undoped samples of HgSe and of HgSe-HgTe alloys containing up to 75 mole % HgTe have been measured at temperatures between 4.2° and 350°K. Undoped samples have negative Hall coefficients over the entire temperature range; at sufficiently low temperatures R_H is independent of temperature, but it eventually decreases with increasing temperature, due to the production of intrinsic carriers. At room temperature the purest samples are in the intrinsic range, since their Hall coefficients are the same at room temperature but different at low temperatures. Although it has not been possible to prepare p-type HgSe, p-type samples with compositions of $HgSe_{0.5}Te_{0.5}$ and $HgSe_{0.25}Te_{0.75}$ have been made by doping with copper, and data on these samples show that the ratio of electron to hole mobility is of the order of 100. Therefore the electron concentration in intrinsic or n-type samples is given by $1/R_He$. The intrinsic electron concentrations at room temperature calculated on this basis range from 4×10^{17} cm^{-3} for HgSe to 7×10^{17} cm^{-3} for $HgSe_{0.5}Te_{0.5}$. The electron mobilities ($R_H\sigma$) for a given carrier concentration do not depend strongly on alloy composition; maximum mobilities of 20 000 and 55 000 cm^2/v sec have been measured at room temperature and 4.2°K, respectively.

* Operated with support from the U. S. Army, Navy, and Air Force.

QA8. Overlapping Bands in HgSe and HgSe-HgTe Alloys. THEODORE C. HARMAN AND ALAN J. STRAUSS, *Lincoln Laboratory,** *M.I.T.*—When the free carrier concentration in a semiconductor increases with temperature, the increase is due either to promotion of intrinsic electrons from valence to conduction band or to ionization of levels lying within the forbidden gap. If HgSe and HgSe-HgTe alloys are assumed to be semiconductors, however, their observed increase in electron concentration with temperature cannot be explained quantitatively by these mechanisms. A satisfactory fit to the data has been obtained by calculating the intrinsic carrier concentrations on the assumption that these materials are semimetals in which the conduction and valence bands overlap in energy. On the basis of magnetoresistance, thermomagnetic effects, and reflectivity data, the conduction band was taken to be spherically symmetric but nonquadratic. The conduction band was assumed to be given by Kane's expression[1] for $E_c(k)$, using the parameters $E_g=0.2$ ev and $P=9\times10^{-8}$ ev cm. The analysis was found to be quite insensitive to the value of E_g. The valence band was assumed to be quadratic. Fermi-Dirac statistics were used. The best fit to the data was obtained for an overlap energy of approximately 0.1 ev and density-of-states hole mass of approximately 0.4 m_0.

* Operated with support from the U. S. Army, Navy, and Air Force.
[1] E. O. Kane, J. Phys. Chem. Solids 1, 249 (1957).

QA9. Dielectric Constant Contribution to the Central Cell Correction for Donors in Germanium and Silicon. KURT WEISER, *IBM Research Laboratories, Yorktown Heights.*—The use of the macroscopic dielectric constant in the expression for the coulombic potential is one of the factors leading to a discrepancy between experimental ionization energies of donors and that calculated from theory. To investigate the dielectric constant behavior near the charge, use can be made of recent work by the author in which calculations were carried out of the dipoles μ induced on the atoms of the crystal by the charge. The results can be used to obtain the local dielectric constant K_l from the relationship $\mu=\alpha q/K_l r^2$, where α is the atomic polarizability and r the distance from the charge q. The dielectric constant resembles a step function having a value of about $\frac{1}{15}$ its macroscopic value up to third nearest neighbors, and then rising steeply to its macroscopic value. With this model, we used a variational method to obtain the minimum in the ionization energy; a hydrogenic wave function was employed with the orbit radius as the variable parameter. The computation gave an ionization energy of 0.0120 ev for shallow donors in germanium. For deep lying donors in germanium and shallow donors in silicon good agreement with experiment was obtained, but the variational method is open to criticism since the effective mass approximation is no longer very satisfactory.

QA10. Cu, Ag, and Au as Deep Acceptor Impurities in InSb.* W. ENGELER† AND H. LEVINSTEIN, *Syracuse University.*—The elements of the Ib column of the periodic table, copper, silver, and gold have been found to act as double acceptor atoms in InSb. Single crystals were grown, using the zone leveling technique with these elements incorporated as impurities. Hall constant measurements were made on samples taken from these crystals, and the activation energies of the impurity levels determined. The values obtained for the lower levels were 0.023, 0.022, and 0.032 ev for Cu, Ag, and Au, respectively. The data obtained for Cu is in agreement with that of Blunt.[1] By compensating the lower levels with Se which is a shallow donor impurity in InSb, the upper ionization energies of these impurities were also observed. This double level picture is consistent with the valence model, the impurity atom acting as a substitutional impurity substituting for the *In* atoms of the lattice.

* Sponsored by Air Research and Development Command, U. S. Air Force.
† Present address: General Electric Research Laboratory.
[1] R. F. Blunt, Bull. Am. Phys. Soc. 3, 115 (1958).

WEDNESDAY AFTERNOON AT 1:30

Terrace Room, Mark Thomas Inn

(J. R. NEIGHBOURS presiding)

Defects in Metals, Annealing

Invited Paper

R1. Diffusionless Phase Transformations. DAVID LIEBERMAN, *University of Illinois.* (30 min.)

Contributed Papers

R2. Annealing of Mono- and Divacancies in Pure Metals.* A. C. DAMASK† AND G. J. DIENES, *Brookhaven National Laboratory.*—The kinetic equations for the simultaneous annealing of mono- and divacancies, including the formation and dissociation of divacancies, have been examined both analytically and on an analog computer. The coupled nonlinear differential

equations were solved in closed form in two approximations: (a) the divacancies are present in small steady state concentration, (b) the vacancies and divacancies remain in equilibrium during the annealing after an initial transient. Neither of these approximations results in a simple decay law nor do they give rise to the initial delay in annealing observed experimentally. However, when the general equations are solved on the analog computer this delay is evident and is physically clearly related to the buildup of divacancy concentration. This is favored by high-divacancy binding energy, high-initial vacancy concentration and low-divacancy mobility (although still higher than single vacancy mobility). The resulting curves cannot be normalized with respect to initial defect concentration and the corresponding complications in deriving an activation energy will be discussed.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† Guest Scientist from Frankford Arsenal, Philadelphia, Pennsylvania.

R3. Vacancy-Interstitial Annihilation with Impurity-Interstitial Trapping.* G. J. DIENES AND A. C. DAMASK,* *Brookhaven National Laboratory.*—As part of the continuing theoretical study[1] of the kinetics of defect annealing in solids, the suggestion of Hasiguti[2] concerning the importance of impurities in the kinetics of interstitial-vacancy annihilation has been examined. Analytical solutions have been obtained in two approximations: (a) low temperature, where binding of interstitial to impurity dominates, (b) high temperature, where decomposition of the impurity-interstitial complex is rate determining. In case (a) the total defect concentration is the reciprocal of a saturating exponential, while in case (b) the decay is a simple quadratic, but only when the initial number of vacancies and interstitials is equal and, therefore, is not simply a result of bimolecular recombination. The solutions for intermediate temperatures can only be obtained numerically. Vacancy-interstitial annihilation in the absence of impurities but with di-interstitial formation and dissociation leads to pure exponential decay in the high temperature approximation. The low temperature behavior is complex.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† Guest Scientist from Frankford Arsenal, Philadelphia, Pennsylvania.
[1] A. C. Damask and G. J. Dienes, Phys. Rev. 120, 99 (1960).
[2] R. R. Hasiguti, J. Phys. Soc. Japan 15, 1807 (1960).

R4. Temperature Dependence of γ-Ray Enhanced Diffusion in α-Brass.* R. E. LARSEN† AND A. C. DAMASK,† *Brookhaven National Laboratory.*—The electrical resistivity decrease associated with short-range ordering in α-brass was measured as a function of time at several temperatures in a 570 000 r/hr Co^{60} source. When both exponential kinetics and appropriate values at infinite time are assumed, the relaxation times are: 2.9×10^6, 1.4×10^6, 0.74×10^6, and 0.223×10^6 sec at 24°, 52°, 75°, and 113°C, respectively. These values yield an activation energy of 5.6 kcal/mol. The theory of radiation enhanced diffusion gives a zero activation energy for the case of linear annealing of the defects, and an activation energy of one-half the migration energy of vacancies for the case of linear annealing plus recombination. Although the linear case was shown to be obeyed under neutron irradiation,[1] the present results seem to fit neither case. Modifications of the theory with respect to γ-ray creation and migration of defects will be discussed.

* Supported in part by the U. S. Atomic Energy Commission.
† Guest Scientists from Frankford Arsenal.
[1] G. J. Dienes and A. C. Damask, J. Appl. Phys. 29, 1713 (1958).

R5. Model for Lattice Defect Recovery in Copper.* A. SOSIN, *Atomics International.*—Modification of the model presented by Hasiguti[1] for lattice defect recovery following radiation damage in copper is discussed. In this model, free interstitials migrate in stage I (<60°K), resulting mainly in interstitial-vacancy annihilation; some interstitials are trapped, the number depending on the concentration of foreign atoms and dislocations. The major release from impurity traps occurs in stage II (~60e to 300°K), resulting in interstitial-vacancy annihilation or further interstitial trapping at dislocations. In stage III (300°K), interstitials are released from particular dislocation regions and migrate further, again leading largely to interstitial-vacancy annihilation. A few interstitials, however, migrate to different dislocation regions where they are more tightly bound, giving rise to the modulus increases observed in stage III. In this model, the observed energy for stage III, 0.60 ev, equals the sum of the free interstitial migration energy, 0.12 ev, plus a dislocation-interstitial binding energy, 0.48 ev. This model is compared with other proposed models.[1,2]

* This research was supported by the U. S. Atomic Energy Commission.
[1] R. R. Hasiguti, J. Phys. Soc. Japan 15, 1807 (1960).
[2] C. J. Meechan, A. Sosin, and J. A. Brinkman, Phys. Rev. 120, 411 (1960).

R6. Effect of Fast-Neutron-Induced Defects on the Internal Friction and Young's Modulus of Pure Copper Single Crystals. D. O. THOMPSON AND V. K. PARÉ, *Oak Ridge National Laboratory.**—The pinning of dislocations, as measured by changes in the modulus and internal friction, can be used to study the mobility of defects produced by irradiation. Specifically, the rate of pinning during fast neutron irradiation at constant temperature is a measure of the number of defects which are mobile enough, at that temperature, to diffuse to the dislocations. This work has been extended so as to cover the range 230° to 350°K in some detail. There is a large release of defects, giving an increasing dislocation pinning rate, between 250° and 300°K. Presumably this corresponds to stage III of resistivity annealing, but the details of the data indicate that a spectrum of processes is involved in the release. Further increases of pinning rate occur in the range 300° to 350°K, as found previously. In all cases the data can be fitted only by assuming that two different types of dislocation are being pinned. The two types differ appreciably in the temperature dependence of their contributions to the modulus and internal friction.

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

R7. Electrical Resistivity Recovery above −80°C in Electron-Irradiated Gold.* R. A. WULLAERT AND J. W. KAUFFMAN, *Northwestern University.*—Gold wire of 99.999% purity was irradiated with 2.4-Mev electrons at about 110°K; the electrical resistivity was measured at 4.2°K following various isochronal and isothermal anneals at temperatures above −80°C. In the isochronal recovery, two major processes were evident between −80°C and the temperature at which complete recovery occurred (+160°C). Stage II recovery was observed up to about −25°C and the fractional recovery corresponded closely to that for irradiations carried out with the specimen temperature near 10°K.[1] Appreciable stage III recovery extended from about −10° to +100°C. Activation energies were determined by the slope intersection method for stage III recovery. The average of eight determinations at temperatures between −5° and +75°C was 0.66 ± 0.05 ev.

* Supported by United States Atomic Energy Commission, and the Advanced Research Projects Agency of the Defense Department.
[1] J. B. Ward, Ph.D. thesis, Northwestern University, 1960.

R8. Effect of Quenching Rate on the Quenched-in Resistivity in Gold.* T. MORI, J. W. KAUFFMAN, AND M. MESHII, *Northwestern University.*—The effect of quenching rate on the quenched-in resistivity in gold was experimentally studied.

For quenching temperatures of 1030°, 900°, 800°, and 700°C a linear relation between the logarithm of quenched-in resistivity and the reciprocal of quenching rate was found, in the range 10^4 to $8(10)^4$°C/sec, which allowed empirical linear extrapolation to infinite quenching rate. The quenched-in resistivity, ρ_∞, obtained by extrapolating to infinite rate, is expressed by $\rho_\infty = A\exp(-E_F/kT)$, where $A = 5.0\times10^{-4}$ ohm-cm and the formation energy, $E_F = 0.97$ ev. With some measurements of volume change of the quenched specimens and with the assumption that a vacancy has 0.4 atomic volume, the following constants are obtained: The resistivity of one atomic percent of vacancies, 1.4×10^{-6} ohm-cm; the entropy of formation of a vacancy, 1.1×10^{-4} ev/°K; and the fractional concentration at the melting point 7.5×10^{-4}.

* Supported by the Office of Naval Research and the Advanced Research Projects Agency of the Defense Department.

R9. Flux and Temperature Dependence of Irradiation-Enhanced Diffusion in Cu-Al. M. S. WECHSLER, R. H. KERNOHAN, AND J. H. BARRETT, *Oak Ridge National Laboratory.**—Irradiation of α-phase Cu-Al neutrons, electrons, and gamma rays produces a decrease in resistivity.[1] A likely explanation is that diffusion is enhanced by the vacancies introduced by the irradiation, which gives rise to short-range ordering and a lower resistivity. If the vacancies are annihilated at fixed sinks, theory[2] predicts that the rate, R, of decrease in resistivity should be proportional to the flux (or, strictly, to the vacancy-production rate, K) and independent of the temperature, T, of irradiation, in agreement with observations on α Cu-Zn.[2] By contrast, our observations on Cu-Al indicate that $R \propto K^{\frac{1}{2}}$ over a range of K from 3×10^{-13} to 1×10^{-9} sec^{-1} at constant T. Furthermore, at constant K, R increases with increasing T. Therefore, using the results of the theory,[2] we conclude that some amount of interstitial-vacancy recombination takes place.

* Operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

[1] M. S. Wechsler and R. H. Kernohan, J. Phys. Chem. Solids **7**, 307 (1958); Bull. Am. Phys. Soc. **5**, 147 (1960).

[2] G. J. Dienes and A. C. Damask, J. Appl. Phys. **29**, 1713 (1958); Bull. Am. Phys. Soc. **5**, 182 (1960).

R10. Clusters of Vacancies in Copper.* George H. VINEYARD AND J. B. GIBSON,† *Brookhaven National Laboratory.*—Characteristics of clusters of vacancies have been calculated in a simple model of copper that contains two-body repulsive forces and a volume-dependent binding.[1] Accepted configurations of the di- and trivacancy have been confirmed, but binding energies (0.06 and 0.5 ev, respectively) are lower. Three forms of stable tetravacancy and three forms of stable pentavacancy have been found. The most tightly bound tetravacancy (0.7-ev binding) is essentially six vacancies on the vertices of an octahedron with two interstitials symmetrically placed near the center. The most tightly bound pentavacancy (1.8-ev binding) is the same set of vacancies with a single interstitial near, but not precisely at, its center. The lack of symmetry was unexpected. Although absolute values of the calculated binding energies are somewhat unreliable because the model is so simple, the high stability of these clusters is thought to be real and to have significance for radiation damage, cold work, and annealing studies.

* Work supported by the U. S. Atomic Energy Commission.

† Deceased.

[1] J. B. Gibson, A. N. Goland, M. Milgram, and G. H. Vineyard, Phys. Rev. **120**, 1229 (1960).

R11. Kinetics of Diffusion Controlled Precipitation in the Presence of Homogeneously Distributed Sources and Sinks. L. A. GIRIFALCO AND D. R. BEHRENDT, *NASA, Lewis Research Center.*—The growth kinetics of a particle in a medium containing homogeneously distributed sources and sinks have been derived by an extension of the methods of Ham.[1] Numerical solutions of the resulting equations have been obtained for three possible mechanisms: (1) Diffusion from a spherical region to a spherical precipitate particle located at the regions center, (2) Diffusion from a sphere to its surface and subsequent instantaneous migration to a precipitate located on the surface of the sphere, (3) Diffusion from a circular two dimensional region to a particle located at its center. For case (1), the radius-time curve is concave to the time axis, the curvature increasing with the efficiency of the sinks. For case (2), the radius-time curve is concave to the time axis, the curvature being large regardless of the efficiency of the sinks. For case (3), the radius-time curve is slightly sigmoid in shape for the short time approximation. The results of this study should be helpful in interpreting the experimental study of some solid state precipitation phenomena such as void growth during plastic deformation.

[1] F. S. Ham, J. Phys. Chem. Solids **6**, 335 (1958).

R12. Void Growth Kinetics in Silver. P. R. OLIVER AND L. A. GIRIFALCO, *NASA, Lewis Research Center.*—Grain-boundary voids which appear when silver is strained at constant rate at diffusion temperatures have been examined to determine the manner of nucleation and growth. Size distributions and void densities for all stages of strain have been obtained. The mean void radius increases linearly with time of strain from a negligibly small initial value, in accord with Girifalco's and Behrendt's theory for bulk-controlled production and diffusion of vacancy-type defects. The growth activation energy of 0.3 ev indicates that divacancies are the probable defects involved. The number of voids per unit volume approaches a constant value as straining proceeds, and this is the number of nuclei existing in the annealed material.

R13. Size Distributions From Small Angle Scattering.* ROBERT H. BRAGG, *Armour Research Foundation.*—The main features of the size distribution in a system of particles (inhomogeneous regions) are revealed by analysis of the function $h^3I(h)$, where $h = 4\pi\sin\theta/\lambda$ and $I(h)$ is the scattered intensity. For nearly-spherical particles a maximum is found for each mode of the distribution (e.g., two peaks for a bimodal distribution) and the location of these maxima are used to determine characteristic sizes for each mode. These sizes are used as a check on the radius of gyration, R, derived from the slope of curves of log $I(h)$ vs h^2. The function $h^3I(h)$ approaches S, the total surface area, for large h provided the experimental conditions approximate infinite slit height collimation. In systems of nonspherical particles the dominant type, i.e., rods, spheres, or plates, is recognized by visual inspection. Other details, such as axial ratios based on an ellipsoidal model of shape are obtained from a simple analysis based on curve fitting.

* Supported by the U. S. Air Force Office of Scientific Research.

WEDNESDAY AFTERNOON AT 2:00

Ballroom, Herrman Hall

(J. GOLDMAN presiding)

Magnetism II

Invited Paper

S1. An Antiferromagnetic to Ferrimagnetic First-Order Phase Transition in $Mn_{2-x}Cr_xSb$. HOWARD J. JARRETT, *E. I. du Pont de Nemours and Co.* (30 min.)

Contributed Papers

S2. Ferromagnetic-Antiferromagnetic Transformation in FeRh. F. DEBERGEVIN, *Institut Fourier, Grenoble,* AND L. MULDAWER, *Temple University.*—Fallot and Hocart showed that FeRh undergoes a sharp decrease in magnetization as temperature is lowered, the transition temperature rising as the rhodium content in FeRh increases. Neutron diffraction studies show that there is a ferromagnetic-antiferromagnetic transformation. Above T_c the structure is CsCl, the magnetic moment of each iron atom being roughly the same as it is in pure iron. Below T_c adjacent iron spins are oppositely directed with the magnetic structure being a NaCl arrangement of magnetic spins. The x-ray diffraction results indicate a cubic unit cell for both states of the alloy; the transformation to the antiferromagnetic state is accompanied by a 0.3% decrease in x-ray lattice constant.

S3. Magnetic Disorder as a First-Order Phase Transition. C. P. BEAN AND D. S. RODBELL, *General Electric Research Laboratory.*—The exchange interaction that gives rise to magnetism depends upon interatomic separation. If the lattice is deformable, then a spontaneous distortion will occur in the magnetic state. We have calculated, in the molecular field approximation, the properties of a system in which the exchange energy dependence is given by $T_c = T_0(1+\beta(v-v_0)/v_0)$. T_c is the Curie temperature appropriate to a lattice volume v while v_0 is the equilibrium volume in the absence of magnetic interactions. The course of the magnetization with temperature of such a system depends upon the steepness β of the exchange interaction dependence on interatomic distance, the compressibility K, and upon T_0. The behavior may be the usual second-order transition to paramagnetism, but it can in fact become a first-order transition with the properties usually associated thereto, e.g., latent heat and discontinuous density change. In the absence of an externally applied pressure, the transition will be of first order if $40\ NkKT_0\beta^2[j(j+1)]^2/[(2j+1)^4-1]>1$.

S4. On the Nuclear Magnetic Resonance of Fe^{57} in Various Ferrimagnetic Oxides. E. L. BOYD, *IBM Research Center,* AND L. J. BRUNER, J. I. BUDNICK, AND R. J. BLUME, *IBM Watson Laboratories.*—The nuclear magnetic resonance of the naturally occurring Fe^{57} nuclei has been observed at room temperature (~23°C) in the ferrimagnetic oxides yttrium iron garnet, gadolinium iron garnet, Fe_3O_4, and $MnFe_2O_4$. The internal fields observed in YIG are in excellent agreement with those reported by Alff and Wertheim.[1] (3.9×10^5 gauss for Fe^{2+} in a tetrahedral site and 4.7×10^5 gauss for Fe^{3+} in an octahedral site.) Their data were obtained by Mössbauer effect measurements which define the site involved as well as measure the field strength. In GdIG we have observed two resonances corresponding to fields of 4.9×10^5 gauss and 4.0×10^5 gauss, respectively. The close correspondence between the two cases suggests that a similar identification of sites involved can be made for both. In the spinel Fe_3O_4 two resonances, yielding internal field values of 4.9×10^5 gauss and 4.6×10^5 gauss, respectively, were observed. Their interpretation will be discussed.

[1] C. Alff and G. K. Wertheim, Bull. Am. Phys. Soc. 5, 428 (1960).

S5. Frequency Dependence of Yttrium Iron Garnet Linewidth. E. H. TURNER, *Bell Telephone Laboratories.*—Measurements of the room temperature linewidth of small polished yttrium iron garnet spheres have been made in the frequency range 9 kMc to 55 kMc. We have used a technique which allows us to measure the same sample over this range. This technique gives either the resonant susceptibility directly or the line width after radiation damping is taken into account. Three varieties of YIG have been used: samples made with highly purified yttrium, samples made with ordinary pure yttrium, and samples with small amounts of rare earth impurities added. With the exception of erbium doped samples, the linewidth has a linear dependence on frequency. At 55 kMc, highly purified samples have a linewidth of less than an oersted, whereas ordinary purity samples have about 2-oe linewidths at this frequency. Rare earth impurities increase the linewidth, and the measured increase can be combined with Kittel's theory to give values of the rare earth relaxation times. Curvature of the ΔH vs H curve in the erbium case can be explained by the fact that the applied field is comparable to the exchange field for this material.

S6. Phonon-Phonon Relaxation during Ferrimagnetic Resonance in YIG. K. DRANSFELD, *Bell Telephone Laboratoires, Inc.*—In ferrimagnets such as yttrium iron garnet the basic cell probably undergoes strong periodic changes during ferrimagnetic resonance even in the absence of macroscopic magnetostriction, as suggested to us by LeCraw. As pointed out recently[1] a deformation of the basic cell at a microwave frequency ω, whether for example produced by rf-electric fields in ionic crystals or by ferrimagnetic resonance in YIG, causes a transient deviation of the phonon distribution from equilibrium. Its re-establishment within a temperature dependent relaxation time τ leads to an increase of entropy and therefore to a ferrimagnetic resonance linewidth ΔH, which would be of the right order of magnitude if one assumed a microscopic magnetostriction similar to that observed by Walsh[2] in $NiSiF_6$. At temperatures above 60°K, when $\omega\tau \ll 1$, one expects ΔH to grow linearly with frequency and with a low power of temperature as measured.[3] As expected, the temperature dependence is the same as found for the far infrared absorption. Below 60°K, however, where $\omega\tau \gtrsim 1$, the frequency and temperature dependence should be quite different.

[1] K. Dransfeld and H. E. Bömmel, Bull. Am. Phys. Soc. 5, 416 (1960).
[2] W. M. Walsh, Jr., Phys. Rev. 114, 1473 (1959).
[3] E. G. Spencer and R. C. LeCraw, Bull. Am. Phys. Soc. 5, 297 (1960).

S7. Relaxation Processes in a Canted Antiferromagnet.* A. J. HEEGER† AND A. M. PORTIS, *University of California, Berkeley.*—The dependence of the microwave resonance spectrum of canted antiferromagnetic $KMnF_3$ on temperature and microwave power has been studied between 1.8°K and 4.2°K. We find a temperature dependence of the resonant frequencies which indicates the development of cubic anisotropy at these low temperatures. At high microwave power levels the resonance lines shift in a way suggesting an increase in lattice temperature. However the shifts are independent of sample size and contact of the sample to the bath. Therefore we must conclude that these shifts result from a magnetic excitation only. Since the temperature dependence of the magnetic anisotropy arises from excitation of the spin wave spectrum, the observed field shifts indicate an effective spin wave temperature above that of the lattice. The relaxation time associated with the observed frequency shift is 60 msec at 1.8°K and decreases inversely as the square of the temperature. By examining the response of a resonance line to power modulation we have found a second relaxation process with a characteristic time of the order of 1 μsec at 1.8°K. This time decreases as $1/T$ at higher temperatures. The line widths are temperature independent, suggesting that the broadening is produced by impurity scattering.

* Supported by the U. S. Atomic Energy Commission.
† National Science Foundation Cooperative Fellow.

S8. rf and dc Magnetic Moments Induced by a Strong rf Magnetic Field Applied Parallel to the dc Field.* E. SCHLÖMANN, *Raytheon Company.*—It was shown previously that spin waves at half the pump frequency become excited if the rf magnetic field exceeds the instability threshold.[1] These spin waves give rise to rf and dc magnetic moments parallel to the dc field. The major part of the rf magnetic moment lags a quarter period behind the rf magnetic field so that the susceptibility is almost purely imaginary. The real part of the susceptibility vanishes unless the frequency of the unstable spin waves differs from half the pump frequency. The dc magnetic moment induced by the rf field is proportional to the power absorbed by the sample. It is always larger than the amplitude of the rf magnetic moment. If the excited spin waves relax via spin-lattice relaxation or via the 3-magnon confluence process,[2] the dc moment induced by the rf field is entirely due to the "first generation" magnons. If the 3-magnon splitting process contributes significantly to the relaxation, however, this moment is enhanced by "second generation" magnons.

* Supported by U. S. ASRDL and ARDC.
[1] E. Schlömann, J. J. Green, and U. Milano, J. Appl. Phys. 31, 386S (1960).
[2] M. Sparks and C. Kittel, Phys. Rev. Letters 4, 232 (1960).

S9. Ferrimagnetic Resonance in Silicon Doped Yttrium Iron Garnet (YIG). J. F. DILLON, JR., *Bell Telephone Laboratories, Inc.*—YIG crystals doped with silicon have been grown (by J. W. Nielsen) in order to force the presence of Fe^{++}. The resonance behavior of these crystals, presumably YIG(Fe^{++}), contrasts strongly with that of pure YIG. Unfortunately, the precise concentration of the operative impurity in any sample is uncertain. Measurements were made of g from H_{res} at two frequencies as well as by the more usual measurements of H_{res} along various crystal directions. Although these gave similar results over a considerable temperature range for pure YIG, for YIG(Si) the two frequency measurements of g gave a consistently lower and anisotropic value. It was found that the impurity has a large effect on H_{res} and ΔH in (110) at 1.5°K. The shape of the curve $\Delta H(T)$ varies considerably with crystal direction. Usually the variation of H_{res} with frequency and crystal direction can be expressed by means of a simple anisotropy surface and an isotropic g. These measurements illustrate a case in which there appear to be an extra dc field in the problem, and also g is anisotropic. It is possible that these two effects can be accounted for by the combined crystal and exchange splitting of the ground multiplet of Fe^{++} in analogy with the YIG(Tb) problem considered by Walker.[1]

[1] L. R. Walker, Bull. Am. Phys. Soc. 5, 418 (1960).

S10. Far Infrared Measurements in Ytterbium Iron Garnet.* A. J. SIEVERS, III, AND M. TINKHAM, *University of California, Berkeley.*—The transmission of ytterbium iron garnet powder has been measured from 100 cm^{-1} to 6.7 cm^{-1}. With the sample at 2°K, transmission minima were observed at 7.1 ± 0.2, 14.1 ± 0.2, 23.4 ± 0.4, and 26.4 ± 0.4 cm^{-1}; the corresponding line widths were 0.6, 1.6, 1.8, and 1.8 cm^{-1}. The two lowest frequencies increased as the temperature was raised to 50°K, while the remaining two frequencies appeared to be temperature independent over the same range. The two high-frequency absorptions have been identified with the exchange splitting of the ytterbium ground state doublet. Two lines are to be expected since the Yb^{+++} ions are distributed in two magnetically inequivalent sites for the spontaneous magnetization along the crystal [111] direction (easy axis).

* Supported in part by the Office of Naval Research, the National Science Foundation, and the Alfred P. Sloan Foundation.

S11. Some Thermodynamic Properties of Ytterbium Iron Garnet. JAMES W. HENDERSON, *Hughes Research Laboratories.*—Some low temperature thermodynamic properties of ytterbium iron garnet have been calculated as functions of temperature and orientation of the magnetization. The partition function used for the calculation considers only the ground state doublets of the ytterbium ions. The anisotropic exchange splittings of these doublets have been determined spectroscopically by K. A. Wickersheim.[1] The calculation accounts for the principal features of the observed torques and specific heats. It predicts the anisotropic free energy, entropy, and magnetization. It also predicts a temperature change accompanying an adiabatic rotation in a saturating magnetic field. This temperature change is large enough to suggest the use of this garnet for refrigeration purposes.

[1] K. A. Wickersheim (to be published).

WEDNESDAY AFTERNOON AT 2:00

King Hall

(H. M. MCCONNELL presiding)

DCP Symposium on Paramagnetic Resonance

T1. Paramagnetic Resonance of the Phosphorescent Triplet State. C. A. HUTCHISON, JR., *University of Chicago.* (30 min.)

T2. Paramagnetic Resonance of Biradicals. S. I. WEISSMAN, *Washington University.* (30 min.)

Business Meeting of Division of Chemical Physics

T3. Nuclear Hyperfine Interactions in Orbitally Degenerate States of Aromatic Ions. A. D. McLachlan, *Harvard University.* (30 min.)

T4. Proton Resonance Shifts in Free Radicals. G. E. Pake, *Stanford University.* (30 min.)

Thursday Morning at 9:30

Terrace Room, Mark Thomas Inn

(Robert F. Landel presiding)

High-Polymer Physics V

Invited Papers

TA1. Factors Influencing the Strength Glassy Polymers. J. P. Berry, *General Electric Research Laboratory.* (40 min.)

TA2. Finite Deformation Theory. P. J. Blatz, *California Institute of Technology.* (40 min.)

Contributed Papers

TA3. Orientation Studies on Drawn Polyolefins.* Joseph Powers, Hiromichi Kawai,† and Richard S. Stein, *University of Massachusetts.*—Polypropylene and polyethylene samples were drawn at a series of elongations and temperatures. The azimuthal variation of x-ray diffraction intensities and the birefringence were determined; orientation functions for crystal axes were calculated and were plotted on triangular orientation diagrams.[1] Polypropylene orients with the *c* axis becoming parallel to the stretching direction while the *a* and *b* axes are arranged randomly about the *c*. With polyethylene, however, the *b* axis becomes oriented perpendicularly to the strecthing direction more rapidly than does the *a* axis. The crystal orientation is better at a given elongation at higher temperatures. The effect of the temperature of crystallization of polypropylene on the crystal orientability indicates that the larger crystals (and spherulites) grown at high temperatures deform with greater difficulty. The crystalline contribution to the birefringence was calculated and compared with experiment, and differences were interpreted in terms of the differences in amorphous orientation.

* Supported in part by a contract with the Office of Naval Research and in part by grants from the National Science Foundation, Plax Corporation and Petroleum Research Fund.

† Present Address: Dept. of Textile Chemistry, Kyoto University, Japan.

[1] R. S. Stein, J. Polymer Sci. **31**, 327 (1958).

TA4. Growth of Crystals from Oriented Amorphous Polyethylene.* Jane Judge and Richard S. Stein, *University of Massachusetts.*—Polyethylene samples were crosslinked by irradiation, cold-drawn different amounts, and then heated while held at constant length. X-ray diffraction intensities and birefringence were observed. From the variation of diffracted intensity with azimuthal angle, orientation functions for the *a* and *c* crystal axes were calculated. The crystalline contribution to the birefringence was calculated and compared with experiment. The initially drawn samples had the *c* axis preferentially oriented at a small angle to the stretching direction. On heating at temperatures below the crystal melting point, the *a* axis remains oriented perpendicularly to the stretching direction, while the *b* axis becomes more strongly oriented perpendicular to the stretching direction. On exceeding the melting point and recooling, the resulting state of crystal orientation depends upon the initial degree of elongation. At low elongations, the *a* axis was preferentially oriented parallel to the stretching direction. At intermediate elongations the *a* axis orients at a preferential angle, while at higher elongations, the *c* axis is preferentially oriented parallel to stretching. The calculated birefringence is consistent with the experimental. An explanation involving competing intramolecular and intermolecular crystallization mechanisms is proposed. Orientation found in commercially extruded films is interpreted in terms of these phenomena.

* Supported in part by a contract with the Office of Naval Research and in part by grants from the National Science Foundation and the Plax Corporation.

TA5. Light Scattering from Spherulitic and Fibrillar Polyethylene.* Marion Rhodes, Philip Wilson, and Richard S. Stein, *University of Massachusetts.*—Previous postulates concerning the origin of the low-angle scattering from spherulitic polyethylene have been tested by an optical diffraction analog technique (though the cooperation of S. Krimm, Dept. of Physics, University of Michigan). A postulated model for the short-range correlation of crystallite orientation within the spherulite which is believed to the responsible for the scattering at greater angles is examined by this technique. A consistent interpretation for the changes in low- and wide-angle patterns occurring upon stretching at a series of temperatures is presented. These reflect the changes from spherulitic to fibrillar morphology. Changes in scattering occurring upon annealing and heat shrinking stretched samples indicate that the annealing process also involves the macro- as well as the microstructure. The scattering patterns may be resolved into two components: (a) the oriented fibrillar-type pattern exhibiting some disorientation resulting from the annealing, and (b) a spherulitic-type pattern. These studies indicate that annealing at temperatures below the melting point involves melting of the more deformed fibrillar structure and recrystallization in a spherulitic form.

* Supported in part by a contract with the Office of Naval Research and in part by grants from the National Science Foundation, the Plax Corporation, and the Petroleum Research Fund.

TA6. Indirect Evaluation of Orientation in Polymers. R. A. Sack,* *British Rayon Research Association* (introduced by R. S. Stein).—As shown by Wilchinsky,[1] for a partially oriented polymer fiber the birefringence of the crystalline phase can, in general, be calculated from a knowledge of the optical properties of the monocrystals and the intensity dis-

tribution of five Debye-Scherrer rings. For crystallites with monoclinic or higher symmetry or lamellar shape, the number of independent orientation measurements reduces to three or two, for hexagonal or needle-shaped crystallites to one. The same number of measurements is needed if the rings contain several unresolved reflexions. If more than the minimum number of observations are available, more accurate results can be obtained by a least square formalism; with composite lines the strongest reflexions do not necessarily possess the highest statistical weight.

* Now at Laboratory of Molecular Structure and Spectra, University of Chicago.
[1] Z. W. Wilchinsky, J. Appl. Phys. **30**, 792 (1959).

TA7. Molecular Weight Distribution from the Normal Coordinate Theory of Viscoelasticity. EMORY MENEFEE, *Western Regional Research Laboratory,** AND WARNER L. PETICOLAS, *I.B.M. Advanced Systems Development.*—The normal coordinate theory for the viscoelastic behavior of polydisperse random coils involves a summation over the integer normal modes of relaxation for each molecule, and an integration over all molecular-weight species present. The distribution of molecular weight may be obtained by inversion of these expressions, using a Stieltjes or Laplace transform for the distribution integral and a novel transform from number theory for the normal mode sum. Certain problems remaining in the theory are discussed.

* A laboratory of the Western Utilization Research and Development Division, Agricultural Research Service, U. S. Department of Agriculture

TA8. Molecular Weight Dependence of the Viscoelastic Properties of Whole Polymers. WARNER L. PETICOLAS, *I.B.M. Advanced Systems Development Laboratory,* AND EMORY MENEFEE, *Western Regional Research Laboratory.**—A general method is presented for correctly averaging component properties to obtain the corresponding property for any mixture of homologous components. The component property is assumed to depend on one or more kinds of average molecular weight and the mixture is assumed to be molecularly homogeneous. The method is applied to determination of the elastic compliance of a mixture, using an equation for component compliance derived from the normal-coordinate theory of viscoelasticity. This provides a reasonable test of that theory, since it examines only the molecular-weight dependence of the theoretical expression. It is shown, in general, that if the component properties depend on higher molecular-weight averages raised to the same power, then the average property can be calculated from easily obtainable quantities.

* A laboratory of the Western Utilization Research and Development Division, Agricultural Research Service, U. S. Department of Agriculture.

THURSDAY MORNING AT 9:30

400 Spanagel Hall

(G. J. DIENES presiding)

Dislocations

U1. Onset of Dislocation Motion in Copper. F. W. YOUNG, JR., *Solid State Division, Oak Ridge National Laboratory.**—Copper (99.999%) crystals with a dislocation density $\sim 10^3/cm^2$ have been prepared. These crystals were stressed by applying a pure bending moment, and the crystals were etched with a dislocation etch either before and after or while the stress was applied. The motion of the dislocations was determined by observing the size and nature of the dislocation etch pits which were formed. It was found that, for a crystal with an initial density of $5\times10^3/cm^2$, the resolved stress necessary to move the old dislocations was 4 g/mm². New (clean) dislocations moved at a lower (undetermined) stress. At a resolved stress of 10 g/mm² some dislocations moved under the stress, then "jumped back" when the stress was removed. Multiplication was observed at a resolved stress of 18 g/mm². Some interesting examples of multiple motion under stress were seen. The observed values of the moving and multiplication stresses are in reasonable agreement with those predicted by theory. Optical micrographs which demonstrate the above points are shown.

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

U2. Supersonic Velocity of Dislocations. MAX SOLOW, *The Martin Company, Balto.*—Eshelby[1] has proved that screw dislocations can move with supersonic velocity. Weertman[2] and others have shown that the maximum possible velocity of dislocations is the transverse velocity of sound. These two resultants are compatible when one realizes that the velocity of medium in which the dislocations are located must be considered. This situation has been analyzed very carefully in fluid mechanics.[3] In the study of shock phenomena the flow is always supersonic with respect to the undistrubed medium, but subsonic with respect to the shocked medium. When one considers a 300 kbar shock in aluminum, the shock velocity is 7.350 km/sec while the particle velocity is 1.465 km/sec. The effective velocity of a disturbance is 5.885 km/sec which is much greater than the transverse velocity of sound 3.733 km/sec. Dislocations cannot move with the above shock wave. Dislocations are complex patterns and cannot nucleate in the shock wave since there is not sufficient time for the information to move. Since the shocked state follows immediately after the shock wave, it is postulated that the shock wave generates vacancies.

[1] J. D. Eshelby, Proc. Phys. Soc. (London) **69**, IC-3, 1013 (1956).
[2] J. Weertman, Phys. Rev. **119**, 1871 (1960).
[3] L. D. Landau *et al.*, *Fluid Mechanics* (Pergamon Press, New York, 1959).

U3. Thermally Activated Dislocation Mobility.* R. THOMSON AND M. MEYER, *University of Illinois.*—The model of Lothe and Hirth[1] has been extended to higher stress regimes where the kink population is highly perturbed by the external stress. The extension over the original model involves a new set of boundary conditions for kink collisions. The results show a linear stress dependence at low stresses which is equivalent to the original treatment of Lothe and Hirth. At higher stresses, the mobility is exponential in the stress. The model is particularly well suited to a crystal like Ge, where the creep data of Van Bueren[2] are adequately described by the theory in terms of the Peierls energy as computed by Celli.[3] Certain types of impurity effects can also be understood in terms of the pinning of kinks on the line.

* Supported by the U. S. Air Force Office of Scientific Research.
[1] J. Lothe and J. Hirth, Phys. Rev. **115**, 543 (1959).
[2] H. G. Van Bueren, Physica **24**, 831 (1958).
[3] V. Celli (to be published).

U4. Frenkel-Kontorova Dislocation in a Discrete Lattice.* ROBERT H. HOBART, *University of Illinois.*—The drag on a moving dislocation due to buffeting by the Peierls hills is studied. Hart[1] has calculated the drag with an assumption that the dislocation motion is inertially dominated. Arguments are given which cast some doubt on this assumption and show it is critical to the results. An alternative approach is proposed and studied in the Frenkel-Kontorova[2] model. A solution to the F-K nonlinear difference equation is obtained. The effect of the Peierls energy can be localized as due to a force on a single central atom. For a moving dislocation this force acts as a source for outgoing radiation. The problem is studied as a driven normal made problem in a continuous F-K model. The point driven responds both inertially and resistively. The latter response is directly related to the loss of translational energy to radiation and thus to the buffeting drag. A nonlinear partial differential equation describing a Peierls-Nabarro model is proposed to serve as the basis of a similar calculation in three dimensions.

* Work supported by the Air Research and Development Command, U. S. Air Force.
[1] E. W. Hart, Phys. Rev. 98, 1175 (1955).
[2] J. Frenkel and T. Kontorova, J. Phys. (U.S.S.R.) 1, 137 (1939).

U5. Dislocation Resistance and Dislocation Morphology in Glide Bands of NaCl Crystals. SOL MENDELSON, *Columbia University.*—Direct observations of dislocations in glide bands were made using a refined birefringence technique and sensitive etch pit method. Glide bands form both slowly ("static bands") and in avalanches ("dynamic bands"). "Static bands" are observed at ~30 g/mm² in crystals of ~10^6/cm² dislocations. The edge dislocations in the band move ~1 mm and the screws ~0.5 mm. "Edge bands" grow in length with increasing stress while growth of the "screw bands" is not detectable before the maximum edge slip distance reaches ~3 mm. The multiplication is then of the "dynamic type" when screw segments cross-slip to neighboring planes and operate as Frank-Read sources. In thin crystals ($t<3$ mm) the "screw bands" extend from one surface to the other and the dislocations in slip planes are in the form of concentric loops having a maximum radius of ~3 mm. When $t>3$ mm, the "screw bands" often stop before reaching the other surface and multiplication on neighboring planes by the cross slip mechanism can occur anywhere along the slip plane resulting in a more complicated dislocation morphology. The slip distance, which depends upon the applied stress, is smaller in high dislocation density crystals and also when flow occured previously or simultaneously on a system oblique to the one under observation. Jogs are the likely resistance to dislocation motion.

U6. Dislocation Damping in Al_2O_3.* R. J. HUBER, G. S. BAKER, AND P. GIBBS, *University of Utah.*—The internal friction of Al_2O_3 has been measured at 50 kc/sec to 1850°C. Undeformed specimens show no damping within the sensitivity of the measurement ($\delta \sim 10^{-5}$). Specimens deformed in tension at 1300°C give an exponentially rising damping above 1400°C with decrements as high as 5×10^{-3} observed. The apparent activation energy for this high temperature damping is approximately 90 kcal/mole. The damping is strain amplitude independent to at least 10^{-5} strain amplitude. The dislocation densities were determined by etch pit techniques. The densities before deformation were approximately 5×10^6 cm^{-2}. Deformation raised this density to as high as 7×10^7 cm^{-2}. The data is analyzed on the basis of three mechanisms: Peierls force, dislocation climb, and impurity dragging. The first two mechanisms appear inconsistent with the data.

* Supported by the Office of Naval Research.

U7. Comparison of Dislocation Patterns in Deformed Pure fcc Metals and α Brass.* J. T. FOURIE, *National Physical Research Laboratory, Pretoria,* AND P. R. STRUTT AND H. G. F. WILSDORF, *The Franklin Institute Laboratories.*—Specimens suitable for diffraction electron microscopy have been prepared from deformed single crystals of aluminum and α brass, the smallest dimension being not less than 10^{-1} cm. In pure fcc metals the majority of dislocations appear as tangles, and many prismatic dislocation loops are found in their vicinity. In contrast, the dislocations in α brass are straight, and large numbers of them are arranged on single slip planes. The difference in the observed patterns can be construed as evidence that the multiplication mechanism is entirely different for these classes of metals. While the operation of single Frank-Read sources could be invoked for α brass, the same mechanism could not account for the majority of dislocations produced in pure fcc metals. The underlying cause for the different behavior of dislocations in pure fcc metals and alloys of α brass type are discussed for the early stages of deformation, and specific mechanisms are proposed.

* This research was supported by the Air Force Office of Scientific Research and the Office of Navel Research.

U8. Generation of Dislocations During Deformation of "Dislocation-Free" Germanium. J. R. PATEL AND A. R. CHAUDHURI, *Raytheon Research Division.*—"Dislocation-free" crystals of silicon and germanium deform at stresses that are orders of magnitude below the theoretically predicted values. This behavior is very probably due to the presence of condensed vacancy loops formed during crystal growth. The dislocation generation stress in a stress-strain test is not only very low but is well defined and depends on the temperature and strain-rate. The generation is not from sources introduced by inadvertent surface damage. The motion of dislocations, from such surface damage sources, occurs at even lower stresses and does not exhibit a sharply defined stress for generation. Furthermore, the motion of dislocations from these grown-in sources is observed to be apparently slower than the movement from a freshly introduced dislocation source, such as a scratch. It is proposed that the pinning of the grown-in source is responsible for the apparently slower motion from the grown-in sources. These observations can be related to the true "delay-time" (as contrasted to the apparent delay time of plastic flow in germanium), which is the time necessary to activate grown-in sources. Measurements of the temperature dependence of this true delay time can be utilized to investigate the defect responsible for pinning such sources.

U9. Apparent Delay Time of Plastic Deformation in Dislocation-Free Germanium. A. R. CHAUDHURI AND J. R. PATEL, *Raytheon Research Division.*—The phenomenon of the delay times during the plastic deformation of germanium under a constant applied stress[1] has been re-examined in terms of the measured dislocation velocities in germanium.[2] The deformation curves of the crystals under constant stress give information on both the delay times and the subsequent strain rates. The dependence of these two parameters on temperature, stress, and doping with electrically active impurities has been determined for initially dislocation-free germanium crystals, as have also the effects of initial dislocation density. In addition, the change in numbers of dislocations with time has been measured. Dislocations are generated, although at a low rate, even during the period of the delay time in initially dislocation-free germanium crystals. The delay time is therefore only an apparent one, and is interpreted as one in which, due to the generation of insufficient numbers of dislocations, there is a very low strain rate. The delay time is terminated when, through dislocation multiplication, the crystal can deform at a sufficiently large plastic strain rate. Both the temperature and stress dependence of the delay time have a similar functional dependence to that of the dislocation velocity on these parameters. The dislocation velocity, therefore, by influencing

the rate of multiplication of dislocations, controls the observed apparent delay time.

[1] C. J. Gallagher, Phys. Rev. **88**, 721 (1952).
[2] A. R. Chaudhuri, J. R. Patel, and L. G. Rubin, J. Metals **12**, 742 (1960).

U10. Self-Diffusion in Germanium Containing Dislocations. H. WIDMER, *I.B.M. Watson Laboratory.*—The diffusion of Ge^{71} in germanium crystals containing dislocations introduced by different methods has been studied using a residual activity technique.[1] The dislocations were introduced by either of the following methods: (1) distorting of the surface by lapping; (2) bending about the [$\bar{1}$12] axis so as to introduce parallel edge dislocations with densities up to 2×10^6 cm^{-2}. The measurements were carried out in the temperature range 720 to 760°C. Both deformation treatments produced an enhanced diffusion relative to results[1] obtained from specimens almost free of dislocations. The penetration curves can, however, in all cases be fitted by an expression for volume diffusion. In the case of specimens deformed by method (1), the apparent diffusion constant is about 40% larger than that for normal bulk diffusion. Annealing at 850°C for 65 hr prior to the diffusion run eliminates this enhancement. In the case of the bent specimens the apparent diffusion coefficient is 20% enhanced for crystals containing 2×10^6 dislocations/cm^2. A comparison will be made with various models for dislocation diffusion.

[1] H. Widmer and G. R. Gunther-Mohr, Helv. Phys. Acta (to be published).

U11. Generation of Point Defects During Plastic Deformation. HOWARD K. BIRNBAUM, *University of Chicago*, AND FLOYD R. TULER, *University of Illinois.*—The generation of point defects during deformation and their subsequent interaction with dislocations has been studied in high-purity copper utilizing the phenomena of strain aging in the temperature range 77° to 273°K. At all aging temperatures, the increase in flow stress on aging, $\Delta\sigma$ (measured at 77°K), exhibited an initial increase which was proportional to (aging time)$^{\frac{1}{2}}$ followed by an exponential decrease with aging time. For constant aging conditions $\Delta\sigma$ was observed to be proportional to the prestrain and to vary as T_t^{-3} (T_t=temperature of testing after the aging treatment). The observations are in agreement with calculations based on an analysis of the increase of point-defect pinning points along dislocations as a result of diffusion of the defects to the dislocations and subsequent diffusion along the dislocations to jogs at which the point defects can disappear. The activation energy for diffusion of the point defects in the lattice is calculated to be 0.12 ev and to be 0.06 ev for diffusion along the dislocation. The point defects appear to retain their identity on arriving at the dislocations rather than nucleating jogs. The mobile point defect has been tentatively identified as the interstitial.

U12. Pressure Dependence of Creep.* K. L. DEVRIES, G. S. BAKER, AND P. GIBBS, *University of Utah.*—Annealed samples about $\frac{1}{4}\times\frac{1}{4}\times\frac{3}{4}$ in. were immersed in a kerosene pressure medium, and stressed in three-point loading by a steel spring when the restraining fuse was melted.[1] Strain was measured by SR-4 strain gauges glued to the tension side of the specimen by Eastman 910 cement. It is estimated that the spring constant changed by less then 3% under application of 10-kbar hydrostatic pressure, and that the applied stress varied by less than 2% during a creep run. A pressure correction of about 20% must be subtracted from the strain gauge reading at 6 kbar. The activation volume for the creep of Sn at room temperature was found to vary between 7 and 9.10^{-24} cm^3 for four pairs of runs below 7 kbar.

* Supported by the Air Force Office of Scientific Research and the Aeronautical Research Laboratory, Air Force Research Division.
[1] Final Report under contract, Aeronautical Research Laboratory, Air Force Research Division, Air Research and Development Command, Wright-Patterson Air Force Base, Ohio (September, 1960).

U13. Work-Softening of Metal Crystals Associated with Temperature, Ultrasonic Radiation, and Rate of Glide Strain. B. LANGENECKER, *Michelson Laboratory, China Lake, California.*—Cottrell and Stokes[1] reported a work-softening of Al single crystals which were work-hardened at low temperatures. This work-softening or sudden reduction of shear stress occurred on subsequent straining at a higher temperature. A second similar effect which produces a sudden reduction of shear stress was reported by Blaha and Langenecker[2] on Al and Zn single crystals when they were alternately loaded with an without ultrasonic radiation of 2 w/cm^2 at a constant temperature. This paper reports a third similar type of work-softening which occurs when changing the rate of glide strain at constant temperature without ultrasonic radiation. This sudden reduction of shear stress appears while straining at a low rate after work-hardening while straining at a high rate. These three types of work-softening are compared and discussed relative to the required energies of deformation and the migration speeds of dislocations.

[1] A. H. Cottrell and R. J. Stokes, Proc. Roy. Soc. (London) **A233**, 17 (1955).
[2] F. Blaha and B. Langenecker, Z. Metallk. **49**, 357 (1958).

U14. Creep of NaCl Single Crystals. C. A. STEARNS, *NASA, Lewis Research Center* (introduced by L. A. Girifalco).—The room temperature compressive creep of NaCl single crystals was studied as a function of applied stress and specimen pretreatment. Over the stress range of 200 to 2500 g/mm^2 and in the time interval 0.01 to 200 min, it was found that the creep curve could be described by two logarithmic equations of the form $\epsilon=A\log t+B$. Complex creep curves showing several stages of creep, such as those observed by Strumane and Dekeyser[1] in tension, were never observed in the present experiments. The creep parameter A was found to be a nonlinear function of stress. Furthermore, above a stress level of about 1200 g/mm^2 this parameter is a sensitive measure of the specimen's surface state.

[1] Strumane and Dekeyser, Acta Met. **7**, 520 (1959).

THURSDAY MORNING AT 9:30

Copper Cup Room, Herrmann Hall

(N. L. OLESON presiding)

Chemical Physics II

UA1. Analysis of the ω Technique[1] of Charge Redistribution for Simple Organic Molecular Systems. S. EHRENSON, *University of Chicago* (introduced by C. C. J. ROOTHAAN).—The empirical LCAO-MO method of Coulomb integral adjustment with charge density, first used by Wheland and Mann[2] and subsequently by others, has been examined in terms of the dependence of convergence upon initial parameter choices. Closed form solutions of the iterative method (to obtain self-

consistent eigenvalues and vectors) for some simple molecular cases provide information on the general validity of this technique. Comparisons may be drawn with other SCF methods such as Pople's.[3]

[1] A. Streitweiser, J. Am. Chem. Soc. 82, 4123 (1960).
[2] G. W. Wheland and D. E. Mann, J. Chem. Phys. 17, 264 (1949).
[3] J. A. Pople, Trans. Faraday Soc. 49, 1375 (1953) and following papers.

UA2. Configuration Interaction in Simple Atomic Systems. A. W. WEISS,* *University of Chicago* (introduced by C. C. J. Roothaan).—The ground-state wave functions of the helium, lithium, and beryllium atoms were approximated by a superposition of configurations with expansion lengths ranging from 35 for helium to 55 for beryllium. The discrepancies in the total energy are 0.014 ev for helium, 0.026 ev for lithium, and 0.17 ev for beryllium. A 19 configuration function was also applied to the lowest ^1S state of helium, with a resulting accuracy of 0.0005 ev. The calculations were also made on all the isoelectronic series of ions through $Z=8$, the discrepancy remaining of the same order of magnitude but increasing with increasing Z. Upper and lower bounds to the electron affinity of lithium are set at 0.4773 ev and 0.6547 ev, respectively, with the most probable value as 0.6158 ev.

* Present address: National Bureau of Standards, Washington, D. C.

UA3. LCAO-MO-SCF Wave Functions for Linear Molecules. E. CLEMENTI AND A. D. MCLEAN, *University of Chicago* (introduced by C. C. J. Roothaan).—Results of a systematic investigation on the ground state LCAO-MO-SCF wave function for the molecules CO_2, HCN, C_3, N_2O, N_3^-, HF_2^-, NO_2^+, OCN^-, SCO, C_4, C_2N_2, and H_2C_2 are presented. All the needed integrals are accurately computed. The basis functions used are Slater-type orbitals. Both minimum and extended basis sets up to 16 basis functions are used. Inclusion of $3d\pi$ and $3d\sigma$ orbitals has been proved to be important to obtain valency and Coulomb polarization. These wave functions are the most accurate attempt yet made to approximate the Hartree-Fock functions for polyatomic molecules. Results obtained with electron population analysis calculations will be presented.

UA4. An LCSTO SCF Calculation of O_2.* S. HUZINAGA, *University of Chicago* (introduced by R. S. Mulliken).—The energies of the ground state $^3\Sigma_g^-$ of O_2 were computed at several interatomic distances by Roothaan's open-shell SCF method. Computations were made automatically by use of the McLean-Weiss Molecular SCF Program written for the Univac 1103 A computor. The basis functions used were $1s$, $2s$, $2p\sigma$, $2p\pi$ and $3d\pi$ STO's (Slater-type orbitals). Our main interest was in the polarization effect of $2p\pi$ due to $3d\pi$. The additional flexibility imparted to the π_u and π_g molecular orbitals yielded improvements of about 2 ev in the total energy and in the binding energy over the case of the so-called minimum set: $1s$, $2s$, $2p\sigma$ and $2p\pi$. Similar calculations were also made for F_2.

UA5. Atomic SCF Calculations in Analytical Form. C. C. J. ROOTHAAN AND M. YOSHIMINE,* *University of Chicago.*†—Hartree-Fock calculations were performed by the expansion method for a number of elements and ions of the first row of the periodic table, using the open shell treatment developed recently by one of us.[1] Considerable experimentation with the basis set was carried out. This demonstrated the need for optimizing the basis set in order to obtain actual Hartree-Fock functions by this method with a reasonably short set of basis functions. Results for a variety of cases will be presented.

* Present address: Argonne National Laboratory.
† The calculations were performed with the support of the Office of Scientific Research, U. S. Air Force, and the Missiles and Space Division of Lockheed Aircraft Corporation.
[1] C. C. J. Roothaan, Revs. Modern Phys. 32, 179 (1960).

UA6. Configuration Interaction Treatment of He_2. PAUL E. PHILLIPSON, *University of Chicago.*—The repulsion energy between two normal helium atoms ($^1\Sigma_g$ of He_2) has been investigated by the method of configuration interaction. The wave function is expressed as a linear combination of determinantal configurations of the form $|\varphi_i\alpha(1)\varphi_i\beta(2)\varphi_j\alpha(3)\varphi_j\beta(4)|+|\varphi_i\alpha(1)\varphi_i\beta(2)\varphi_j\alpha(3)\varphi_j\beta(4)|$ where the φ's are symmetry orbitals constructed from Slater-type atomic orbitals ($1s$, $1s'$, $2p\sigma$, $2p\pi$). At several internuclear distances R between 0.5 A and ∞, the orbital exponents were independently varied to minimize the energy for a chosen set of configurations. Various types of wave functions were tried varying from one to 64 configurations. It was found that between 0.5 A and ∞ the repulsion energy (the difference between the energy at a given R and the separated atom energy) is quite constant at a given R over a range of optimized wave functions of various degrees of goodness. It appears that any improvement in the energy at a given R is compensated for by a quantitatively similar improvement in the separation energy so that the repulsion energy remains essentially the same. At 0.5 A, a repulsion energy of 27.71 ev was calculated using a 64-configuration wave function, and all wave functions tried gave an energy within 0.9 ev of this figure.

UA7. Fine and Hyperfine Structure of the Metastable $^3\Pi_u$ State of the Hydrogen Molecule. M. MIZUSHIMA AND D. A. FREY, *University of Colorado.*—The spin-orbit coupling constant and the hyperfine coupling constants for the $2p^3\Pi_u$ state has been calculated by using Amemiya's wave function.[1] The lowest state is expected to be ($K=1$, $J=2$), while ($K=1$, $J=1$) and ($K=1$, $J=0$) states have energies of 7500 Mc and 11500 Mc, respectively. The hyperfine coupling terms are $-8I_z-18S_zI_z+503\mathbf{S}\cdot\mathbf{I}$ Mc, where z is the molecular axis to the direction of Λ. The hfs of $K=1$ states are calculated. The transition within each fine structure level can occur through proton magnetic moment and their frequencies are expected to be 750, 500, and 250 in Mc. They are the lines which correspond to the 1420-Mc line of the atomic hydrogen. The metastability of this state has been demonstrated by Lichten,[2] but the lifetime is expected to be much longer than he thought. Thus it seems to be possible to observe the rf spectrum calculated here either in outer space or artificially excited hydrogen gas.

[1] A. Amemiya, Proc. Phys.-Math. Soc. Japan 21, 394 (1939).
[2] W. Lichten, Phys. Rev. 120, 848 (1960).

UA8. Electronic Structure of Decaborane. EMMETT B. MOORE, JR., *Boeing Scientific Research Laboratories,* AND WILLIAM N. LIPSCOMB, *Harvard University.*—An LCAO treatment of the 22 framework atomic orbitals and 16 framework electrons of decaborane yields eight bonding MO's which have energies between -16.6 ev and -5.7 ev and which are separated somewhat in energy from the other MO's. Allowed transitions correspond closely to the maxima in the observed absorption and luminescence spectra. An electron population analysis yields a charge of $+0.27e$ on atoms 6 and 9, $-0.25e$ on 2 and 4, $+0.05e$ on 1 and 3, and $-0.03e$ on 5, 7, 8, and 10, and gives a dipole moment of $3.6D$, compared with the experimental dipole moment of $3.5D$. If $-0.2e$ is assigned to each bridge hydrogen atom, this charge distribution agrees satisfactorily with the charge distribution inferred from the reactions of decaborane. Distribution of the charges into hybrid orbitals and electron repulsions were neglected.

UA9. Jahn-Teller Distortions of Large Aromatic Radical Anions: a Molecular Orbital Description. L. C. SNYDER, *Bell Telephone Laboratories, Inc.*—The Jahn-Teller instability of the symmetrical forms of the triphenylene, *sym*-triphenylbenzene, coronene, and cyclooctatetraene mononegative ions, with respect to a complete set of bond length displacements for each, has been given a Huckel approximation molecular

orbital description with an iterative computational procedure.[1] For each radical anion, the energy, spin densities, bond lengths, and charge distribution have been computed for the symmetrical configuration of minimum energy and for distorted configurations of stationary energy. The basic assumptions of both Lennard-Jones and of Longuet-Higgins and Salem have been adopted for the resonance integral and sigma framework description.[1,2] Under the Lennard-Jones assumptions the energy change on distortion to a configuration of minimum energy is respectively −0.73, −0.68, −0.56, and −2.35 kcal/mole for the four mononegative ions. Under the Longuet-Higgins and Salem assumptions, the energy changes upon distortion are about half as large. The electronic structures of both coronene and triphenylene negative ions interact with a degenerate pair of bond length displacements but show negligible evidence of energy saddle points.

[1] L. C. Snyder, J. Chem. Phys. 33, 619 (1960).
[2] W. D. Hobey and A. D. McLachlan, J. Chem. Phys. 33, 1695 (1960).

UA10. Self-Consistent Field Approach to the Quadrupole Polarizability of Ions. A. J. FREEMAN, *Ordnance Materials Research Office*, AND R. E. WATSON,* *AVCO, R.A.D.*—The problem of the polarization of electron shells of ions by external charges has been treated by first order perturbation theory in two distinct ways: (1) exact numerical solution of the inhomogeneous wave equation for the perturbation of the wave function, as was done by Sternheimer and collaborators and (2) the variational approach of Das and Bersohn in which the perturbed wave function is first parameterized and the parameters determined by minimizing the perturbation energy. We are reporting calculations of the quadrupole moment induced in the electron shells of an atom by an external charge using an extension of the Hartree-Fock self-consistent field method for atoms. The quadrupole field of the external charge is included in the H-F equations which are then solved by allowing the electrons in a shell with different m_l to have different radial wave functions. In this way the Sternheimer "radial" quadrupolarizabilities of Cu^+ and Cl^- were determined and compared with the results reported using methods (1) and (2) above. In each case the computed polarizability is greater than those reported earlier, and this may be explained as arising from the effect of the perturbed outer wave functions on the inner shell electrons.

* The work of this author was supported in part by the Ordnance Materials Research Office.

UA11. Spin-Orbit Coupling for Open-Shell Configurations Containing More Than One Particle.* GORDON L. GOODMAN, *Argonne National Laboratory*.—Only for one charged particle moving relatively slowly in a central field can $\zeta \mathbf{l}\cdot\mathbf{s}$ be a proper description of H^I, the spin-orbit interaction; ζ being assumed independent of all angular and spin variables. For open-shell configurations containing more than one charged particle, coupling of the spin of each particle with its own orbital angular momentum is influenced by correlations that exist between motion of this particle and motions of others. Accordingly, the following form for H^I is suggested in N-particle systems: $\hat{H}^I = \frac{1}{2}\sum_{i=1}^{N}\{(1/r)(\partial/\partial r)V,\ \mathbf{l}\cdot\mathbf{s}/(2\mu^2c^2)\}_i$, where $\{a,b\}_i = a_ib_i + b_ia_i$ and $V_i = V_{\text{central}}(r_i) + \sum_{j\neq i}^{N} e^2/r_{ij}$. In the Russell-Saunders limit, $\hat{H}^I$ preserves Landé's interval rule; however, even for two equivalent fermions (d-electrons, say), the Landé constants for various triplets are generally unequal and *not* the only independent spin-orbit parameters (as one can verify by expanding $1/r_{12}$ in terms of Legendre polynomials). King and Van Vleck profitably used a correction equivalent to $\hat{H}^I$.[1]

* Work under auspices of the U. S. Atomic Energy Commission.
[1] G. W. King and J. H. Van Vleck, Phys. Rev. 56, 464 (1939).

UA12. Study of Small Atoms by Perturbation Theory. JAN LINDERBERG, *University of Florida* (introduced by P. O. Lowdin).—Energy corrections of the second order have been evaluated by means of variational methods and a technique used earlier by this author.[1] One part of the correction corresponds to a Hartree-Fock type calculation and a second part gives two-particle correlation energies. The first contribution is evaluated exactly and the second is estimated by simple variational calculations.

[1] J. Linderberg, Phys. Rev. 121, 816 (1961).

UA13. Master Equation for Dense Gases and the Approach to Equilibrium. FRANK C. ANDREWS,* *University of California, Berkeley*.—A generalized form of the Master equation for the evolution of the velocity distribution function in a dense gas is given. This is a form which is conveniently formulated from the Liouville equation, and its physical meaning of being a Master equation in the usual sense is shown. It is shown that the scattering term monotonically drives an arbitrary velocity distribution function to a function of the unperturbed Hamiltonian. Such a function (of the unperturbed Hamiltonian) is the unique stationary solution of the Master equation. The proof is thus a generalization of Boltzmann's H-theorem.

* National Institute of Health Research Fellow.

UA14. Law of Corresponding States for Fused Salts.* H. REISS AND S. W. MAYER, *Atomics International*, AND J. KATZ,† *University of Chicago*.—Reduced equations of state have been developed for a large class of fused salts through appropriate analysis of the configuration integral. The theoretical results are supported by experiment for highly polar substances. Typical relations obtainable by these methods are the following:

For symmetrical salts the melting points, T_m, are given by $T_m = (z/\lambda)(3.19\times10^{-8})$ deg °K where z is the valence and λ is the sum of the ionic radii in cm. For the surface tension, σ_m, at the melting point, $\sigma_m = (3.26\times10^{-21}/\lambda^3)$ dyne cm^{-1} and $\sigma_m = (1.03\times10^{-7}T_m^3)/2$ dynes/cm. One reduced equation of state is

$$\pi'' = \pi''(\tau'',\nu''), \quad \text{where} \quad \pi'' = \frac{z^3}{T_m^3}p, \quad \tau'' = T/T_m, \quad \nu'' = \frac{T_m^3}{z}V.$$

This is satisfied very well by polar symmetrical salts. Relations for unsymmetrical salts are also derived.

* This work supported by U. S. Atomic Energy Commission.
† American Chemical Society Petroleum Research Fund Predoctoral Fellow.

THURSDAY MORNING AT 9:30

421 Spanagel Hall

(H. MEDWIN presiding)

Surface Phenomena and Crystal Growth

V1. A Melting Model.* RICHARD C. SILL, *University of Nevada* AND S. A. GOUDSMIT, *Brookhaven National Laboratory*.—In the equilibrium position a lattice molecule B midway between its neighbors A and C will be in a deep potential minimum. For Lennard-Jones potentials a small outward displacement of A and/or C caused by thermal vibrations pro-

duces a "hump" at this minimum, and then molecule B has two equilibrium positions, one near A, one near C. We believe that the occurrence of this "hump" is connected with the onset of melting. When A is a surface molecule, less energy is needed to produce the "hump" at B than for interior molecules. This may explain why melting starts from and is strongly influenced by the surface. The needed energy is related to the constant ϵ of the Lennard-Jones potential. It can be expressed as a temperature by crudely assuming equipartition, as if the vibrations were harmonic. This gives $kT_m \gtrsim 0.5\ \epsilon$. In this preliminary heuristic treatment we have omitted the still unexplained cooperative and statistical aspects of the melting process. Nevertheless, in many cases T_m is near the observed melting temperature.

* Supported in part by the U. S. Atomic Energy Commission and the Research Corporation.

V2. Corner Nucleation in the Oxidation of Germanium. JACOB F. DEWALD, *Bell Telephone Laboratories, Inc.*—Ligenza's application of the Cabrera-Mott theory of thin-film oxidation to germanium gives a frequency factor 10^{12} smaller than those observed on metals. Part ($<10^3$) of this anomaly arises from the substrate's semiconducting nature. The major factor arises from high-crystal perfection and low-coordination number. These force the germanium atoms to leave only from two-bonded sites and on {111}-bounded crystallites require corner nucleation. Oxidation proceeds as n cars (initially touching) would move on a single track if they took unit steps forward with random phase and equal probability (if not obstructed). The probability of attaining the configuration $(N_1 N_2 \cdots N_n)$ is

$$P(N_1 N_2 \cdots N_n) = \prod_{i=1}^{n} (N_i + n - i)!/(\sum_{i=1}^{n} N_i)! \prod_{i<j>1}^{n} (N_i - N^j + j - i). \tag{1}$$

N_i is the number of steps taken by car i. The most probable configuration has car number $(2N_1^1)$ as the first obstructed car. This result is used to account for most of the remaining anomaly.

V3. Point Defect Trapping in Crystal Growth. W. W. WEBB, *Union Carbide Metals Company.*—Whether appreciable nonequilibrium concentrations of point defects can be trapped in crystals during near-equilibrium growth has been considered. A semiquantitative treatment based on the established theory of near-equilibrium growth on vicinal surfaces indicates that either a supersaturation or undersaturation of point defects may result from near-equilibrium growth. A dimensionless parameter D_v/Rd where D_v is the diffusion coefficient for point defects, R is the growth rate, and d is the effective interface thickness, describes most of the relevant features of the growth conditions. At temperatures well below the crystal melting temperature large supersaturations may be trapped but near the melting point only small undersaturations may be retained. The effects of growth-trapped point defects on subsequent dislocation climb appear to be significant in solution-grown crystals, in metal whiskers, some vapor-grown crystals, and possibly in melt-grown crystals.

V4. Mechanism for Facet Generation in Diamond Lattice Dendrites. D. R. HAMILTON AND R. G. SEIDENSTICKER, *Westinghouse Research Laboratories.*—The interface of a diamond lattice dendrite growing in a semi-infinite supercooled melt is considered theoretically to be composed of three regions: the tip, where the twin plane propagation takes place[1]; in intermediate or transition region, discussed in this paper, and the "H" are region[2] in which lateral growth is accomplished. A growth mechanism operative in the transition region is described which depends upon a supercooled melt and also upon the existence of distinguishable growth events on the interface. It is shown that these conditions lead to steady state oscillations in growth which could result in periodic formation of microscopic facets. The development of these facets through the onset of lateral growth is considered.

[1] D. R. Hamilton and R. G. Seidensticker, J. Appl. Phys. 31, 1165 (1960).
[2] J. W. Faust, Jr., and H. F. John, Bull. Am. Phys. Soc. 5, 165 (1960).

V5. Nonequilibrium Crystallization of KNO_3-$Ca(NO_3)_2$ Mixtures at Temperatures Immediately above the Glass Transformation. ALDEN B. BESTUL, *National Bureau of Standards.*—KNO_3-$Ca(NO_3)_2$ mixtures readily form glasses in the composition range around 44 to 58 wt % $Ca(NO_3)_2$. The glass transformation temperatures (T_g) range from around 40 to 70°C. This composition range encompasses the mixture of 45.8 wt % $Ca(NO_3)_2$ which forms an eutectic at 146°C. The primary crystalline phases are $Ca(NO_3)_2$ and $4KNO_3 \cdot Ca(NO_3)_2$. The liquidus temperatures in the above composition range vary from that of the eutectic to about 165° for $4KNO_3 \cdot Ca(NO_3)_2$ and liquid and about 285° for $Ca(NO_3)_2$ and liquid. The crystallization rates of these primary phases have previously been studied by Dietzel and Poegel in the temperature regions of their maxima, which occur around 50–80 degrees below the liquidus temperatures. The present author has now investigated crystallization rates for the mixture of 58 wt % $Ca(NO_3)_2$ at temperatures between 70 and 110°. The crystals formed apparently represent some kind of precipitation of the mixture in the composition ratio present in the super-cooled liquid. In partially crystallized samples the T_g of the remaining uncrystallized portion is independent of the extent of crystallization from 0 to essentially 100%. The T_g's are the same as that for the completely uncrystallized material. The rate of crystallization increases monotonically with increasing temperature, and shows no maximum in the temperature range investigated.

V6. Temperature Dependence of the Neutron Scattering of Palladium Containing Absorbed Hydrogen. A. I. SCHINDLER AND G. A. FERGUSON, *U. S. Naval Research Laboratory, Washington, D. C.*—An anomalous peak at 50°K in the electrical resistivity of palladium containing absorbed hydrogen has been reported by Schindler, Smith, and Kammer. They have suggested that this anomaly results from either the disordering of the hydrogen ions, the existence of an antiferromagnetic transition, or a structure change. Since neutron diffraction is sensitive to all three types of transitions, such measurements were carried out as a function of temperature on a fully hydrogen charged sample of palladium. Measurements were made at 4.2°, 50°, 77°, and 300°K. The 300°K data agree well with the results previously reported by Worsham, Wilkinson, and Shull. As the temperature was lowered to 4.2°K, no new strong lines appeared between the scanned counter angles of 26° and 90°. This result seems to rule out the existence of a simple antiferromagnetic transition or a structure change. However, the temperature dependence of the coherent nuclear scattering of palladium in the (111) peak showed an anomalous behavior. It increased as the temperature was lowered from 300° to 77°K, then decreased as the temperature was further lowered to 50°K, and again increased at 4.2°K. This dependence also suggests a hydrogen ion disordering at 50°K. In the vicinity of the (111) peak, the spin incoherent nuclear scattering of the hydrogen ions at helium temperatures is approximately 10% above that observed at the higher temperatures.

V7. Annealing Characteristics of Evaporated Germanium Layers. R. F. POTTER, R. L. BATES, AND R. J. MACEK, *U. S. Naval Ordnance Laboratory, Corona.*—When germanium condenses from the vapor state it forms either a crystalline or an amorphouslike layer depending upon the substrate temperature; the crystalline layers forming at temperatures between

250° and 300°C and above. Amorphouslike layers of Ge were formed on glass substrates at 200° and −25°C, and the annealing and tempering characteristics studied by means of x-ray diffraction and infrared interference effects. Annealing temperatures have been in the range between 300° and 450°C. Changes in crystallinity were observed by measuring the integrated line intensity of the (111) planes at $2\theta = 27.3°$ following each annealing period. An analysis of the results indicate that the films become crystalline as a result of a series of first order reactions with a range of activation energies. Interference effects indicate a thickness decrease in the films of as much as 15% during the period of crystallization with a negligible change in film mass, giving further evidence of the initial presence of a highly distorted lattice.

V8. Observations on Individual Adsorbed Atoms.* GERT EHRLICH AND F. G. HUDDA, *General Electric Research Laboratory.*—The interactions of nitrogen with a tungsten surface have been studied in Müller's field ion microscope, with a resolution of less than 5 A. Adsorption at 300°K results in a nonuniform distribution of adatoms with the highest concentration in the jogged regions between the 100 and 111 zones. During the initial stages the more closely packed planes, such as (110) and (211), remain devoid of gas. This distribution is dictated by the kinetics of the dissociation step and not by variation in the binding energy of adatoms. At 300°K the adatoms appear fixed in place; extensive rearrangement is only observed at $T > 400$°K. The configuration of surface atoms from which a nitrogen atom has moved on heating is identical with that prior to adsorption, indicating that no permanent perturbation of the lattice occurs. At 300°K adsorption of nitrogen is not observed on pairs of nearest neighbor sites. Instead, adatoms are separated by several lattice spacings. This suggests that in the dissociation of the molecule vibrationally excited adatoms are formed which can migrate before decaying to their ground state.

* This work was supported in part by the Air Force Office of Scientific Research, Washington, D. C.

V9. ac and Pulsed Effect Investigation of the Iodine Etched Germanium Surface. W. J. HEINECKE, *Transitron Electronic Corporation* (introduced by David Navon).—Surfaces resulting from the reaction between gaseous iodine and single crystal germanium were investigated. Surface trap population data derived from ac field effect data show a definite aging effect of the *N* type surface resulting from etching. Such aging occurs in air, dry nitrogen or vacuum. Energy level, capture cross section, and density are established through pulsed field data taken at various temperatures.

V10. Characteristics of Indium Films Deposited in the Presence of Various Residual Gases. HOLLIS L. CASWELL, *IBM Research Laboratory, Yorktown Heights.*—Indium films have been evaporated at pressures less than 10^{-9} torr and at higher pressures of specific residual gases. N_2, H_2, CH_4, Ar, CO, and CO_2 were found to have no measurable effect on the electrical or superconducting properties of these films when present in partial pressures of 10^{-5} torr. For oxygen a pronounced effect was observed when k (the ratio of oxygen molecules to indium atoms striking the substrate) exceeded 3%. The room temperature resistivity increased from 9.0 μ-ohm-cm to 14 μ-ohm-cm, the critical temperature decreased from (3.40 ± 0.005)°K to (3.389 ± 0.002)°K, the effective magnetic penetration depth increased from 630 ± 100 A to over 1000 A. For $10^{-3} < k < 3 \times 10^{-2}$ a larger apparent penetration depth was observed for films deposited through a mask due to edge effects. It was shown that indium films could be deposited at 100 A/sec on clean, baked substrates at 10^{-8} torr with characteristics indistinguishable from those of films deposited in ultra-high vacuum provided the partial pressure of oxygen was less than 10^{-7} torr and that of water vapor less than 10^{-8} torr.

V11. (Abstract withdrawn.)

V12. Ion Bombardment of Ag from 2-50 kev. FRED E. HOLMSTROM AND ROBERT D. KNIGHT, *IBM Research, San Jose.*—Polycrystalline Ag targets have been bombarded with He and Ar ions using the beam system described earlier.[1] Material sputtered from a 3-mm target of radio-active Ag electroplated on Pt foil was collected on two substrates circularly positioned above the target surface. Intensity profiles of ejected target material were obtained over the entire 180° by sectioning the substrates and measuring the activity of segments corresponding to regular angular positions. No intensity increase was observed in the forward direction for incident angles up to 60° from the target normal. However, for bombarding angles greater than approximately 45°, a reverse effect, i.e., a higher intensity in the reverse direction than in the forward direction, was observed when using electroplated targets receiving no surface treatment prior to bombardment. Pronounced "over cosine" profiles were observed at normal incidence for ion energies up to 50 kev as reported,[2] becoming more cosine as the practical lower limit of 2 kev for this system was approached. Various noble gases are being used to bombard high purity polycrystalline Ag targets approximately 1 mm in diameter with the surface being treated in a variety of ways prior to use.

[1] Fred E. Holmstrom and Robert D. Knight, Bull. Am. Phys. Soc. 5, 503 (1960).
[2] G. K. Wehner and D. Rosenberg, J. Appl. Phys. 31, 177 (1960).

V13. "Nickelate" Cathode in Gas Tubes. ROBERT W. STRECKER, *National Electronics Corporation* (introduced by R. G. POHL).—There has been little published data on the "nickelate" cathode other than that in Edwards' original patents.[1] Years of experience with this cathode in gas tubes has shown it is superior to the oxide cathode with regards to low-grid emission and high-sputter resistance, although the exact reason has remained unknown. It has been determined that the degree these advantageous properties exist in the cathode is fixed by the time and temperature of the initial melt of the nickel oxide and barium oxide mixture that makes up the cathode coating.

[1] D. V. Edwards and E. K. Smith, U. S. Patent 1,985,855 (1932), and U. S. Patent 2,081,864 (1934).

V14. Constituents of "Nickelate" Cathodes and Changes in Matrix Cathodes due to Ion Bombardment.* ROBERT G. POHL AND BERNADINE TOOPER, *Armour Research Foundation of Illinois Institute of Technology.*—X-ray and electron dif-

fraction studies of "nickelate" cathodes show that cathodes that have been processed so as to obtain high sputter voltages and high thermionic emission do not contain the compound barium nickelate. Rather the finished cathode consists of a matrix cathode wherein barium oxide and other barium compounds are distributed within a nickel matrix. The nickelate melt phase of the processing serves as a solvent permitting solution of barium compounds into the nickel substrate. Subsequent processing decomposes barium nickelate out of existance. The finished cathode is a matrix cathode possessing a more homogeneous distribution of constituents than obtained in the customary sintered bariated nickel matrix cathode. A study of the darkening due to ion bombardment of bariated nickel matrix cathodes employed in high-power klystrons shows an excess of calcium in the darkened area, together with the formation of tungstates and zirconates, and the loss of reducing agent, zirconium.

* Research supported by U. S. Air Force through Rome Air Development Center, Air Research and Development Command.

THURSDAY MORNING AT 10:00

Ballroom, Herrman Hall

(L. BICKFORD presiding)

Magnetism III, Insulators II

VA1. Specific Heat of Nickel Ferrite at Liquid-Helium Temperatures.* S. R. POLLACK, *University of Pennsylvania* (introduced by Norman Goldberg).—The specific heat of a polycrystalline sample of $NiFe_2O_4$ [1] has been measured in the liquid-helium temperature range in order to measure the magnon contribution to the specific heat and its temperature dependence. Our data can be well represented by the relation $C=0.405\pm0.008T^3+0.0576\pm0.001T^5\times10^{-3}$ joules/mole °K, where the coefficients of the temperature were determined by a least-squares fit of C/T^3 vs T^2. The coefficient of T^3 can be determined by spin-wave theory in terms of the Landau-Lifshitz exchange constant A. A was found to be $(3.59\pm0.07)\times10^{-7}$ erg/cm. The coefficient of T^5 was used to determine the Debye temperature, Θ_D, which is $\Theta_D=618°K\pm4°K$. The value of the Debye temperature is in good agreement with the value obtained by E. G. King at 77°K, namely, 570°K. The value of A obtained is smaller than that obtained by Guillaud and Roux from M_s vs T curves. Their value of A was 9.0×10^{-7} erg/cm. A similar disagreement exists between A for magnetite obtained by Kouvel from specific heat measurements and by Weiss and Forrer from magnetization data. Specific heat data has been taken on magnesium, cobalt, and lithium ferrites in order to see if similar discrepancies occur for these ferrites. This data is in the process of analysis.

* This project supported by the Office of Naval Research.
[1] Made by Remington Rand Univac, Division of Sperry Rand Corporation, Philadelphia, Pennsylvania.

VA2. Magnetic Properties of $HCrO_2$ and $DCrO_2$. R. G. MEISENHEIMER AND J. D. SWALEN, *Shell Development Company, Emeryville.*—Magnetic susceptibility measurements and electron paramagnetic resonance measurements have been made on powdered chromous acid ($HCrO_2$) and deuterated chromous acid ($DCrO_2$). The Curie constants, derived from the susceptibility results, are consistent with three unpaired electrons associated with each chromium ion. In addition, a large Curie-Weiss θ temperature, indicating a strong exchange interaction, is necessary to account for the results. The most unusual feature of this particular exchange is that it is strongly influenced by deuteration. The electron paramagnetic resonance spectra also show strongly exchange narrowed lines with a variation between $HCrO_2$ and $DCrO_2$. From a comparison between the calculated and observed line widths and second moments, a value of the zero field splitting is estimated. Although no transition has been observed to an antiferromagnetic state, the Curie-Weiss θ temperatures indicate that the ground state is undoubtedly antiferromagnetic for both $HCrO_2$ and $DCrO_2$. Superexchange through the intervening proton or deuteron is probably the main source of any antiferromagnetic exchange coupling. Some of the various mechanisms proposed for superexchanged are discussed in relation to chromous acid.

VA3. Magnetic Structure of Anhydrous Sulphates of the Iron-Group Elements.* B. C. FRAZER AND P. J. BROWN, *Brookhaven National Laboratory.*—The anhydrous sulphates of iron, cobalt, and nickel become antiferromagnetic at temperatures in the range 15°–37°K.[1] The magnetic structures of these compounds have been determined using neutron diffraction data from powdered crystals taken at room temperature and at liquid-helium temperature. These compounds are isomorphous with one another and with $CrVO_4$,[2,3] the antiferromagnetic structure of which is formed from alternating ferromagnetic sheets of Cr^{3+} ions on (002) planes. In these sulphates, however, the ions in sheets on (002) planes are coupled antiferromagnetically. The Fe and Ni ions are found to have their spins oriented parallel to [010] and successive sheets in $FeSO_4$ and $NiSO_4$ are coupled ferromagnetically. The spin on the Co ion in $CoSO_4$ is found to be inclined at $78°\pm2°$ to [001] in the (100) plane and in successive sheets the inclination is alternately clockwise and anticlockwise from the [001] axis. The numerical values determined for the magnetic moments are close to those expected for divalent iron, cobalt, and nickel ions.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] A. S. Borovik, V. R. Karasik, and N. M. Kreines, Zhur. Eksptl. i Teoret. Fiz. 31, 19 (1956), [English translation: Soviet Phys.—JETP 4, 109 (1957)].
[2] P. I. Dimaras, Acta Cryst. 10, 313 (1957).
[3] J. Coing-Boyat, Acta Cryst. 12, 939 (1959).

VA4. Coercive Force, Magnetization Energy, and Implied Anisotropy of Uranium Hydride and Uranium Deuteride. WARREN E. HENRY,* *U. S. Naval Research Laboratory.*—Extension of the magnetization studies[1] of uranium hydride and uranium deuteride has lead to a study of the builtin constraints on the free rotation of the magnetic dipoles in UH_3 and UD_3. The magnetization measurements were carried out in the usual way by sample displacement, with respect to a coil system, and the moment measured ballistically. Calibration was carried out with pure nickel. Field sweeps through zero from +70 000 gauss to −70 000 gauss and through a cycle have yielded results on the coercive force, remanence, and ferromagnetic interaction of UH_3 and UD_3. The remanent magnetizations of UH_3 are: 0 at 295°K; and (as H=zero is approached) 0.2 Bohr magneton per atom of uranium at 77.4°K (at $H=+0$) and 0.5 at 77.4°K (at $H=-0$); at 4.2°K the remanent magnetization is 0.7 Bohr magneton per atom

of uranium and for 1.3°K, the results are the same as for 4.2°K. The coercive forces are 0 for 295°K; 2700 gauss for 77.4°K at ±0, 4100 gauss at 4.2°K and 4100 gauss at 1.3°K. A tenth-power dependence of the saturation magnetization on temperature gives an indication of the temperature dependence of the anisotropy energy of uranium hydride. The energy of magnetization is $\sim 10^7$ ergs/cm³. Uranium deuteride exhibits similar behavior to that of uranium hydride.

* Present address: Lockheed Missiles and Space Division, Palo Alto, California.
[1] W. E. Henry, Phys. Rev. 109, 1976 (1958).

VA5. Static Dielectric Constant of Rutile (TiO_2), 1.6°–1060°K. REBECCA A. PARKER, *National Bureau of Standards* (introduced by H. P. R. Frederikse).—The static dielectric constant ϵ of rutile (TiO_2) has been measured as a function of temperature from 1.6° to 1060°K. Rutile does not appear to be ferro- or antiferroelectric in this temperature range. At low temperatures, ϵ approaches a limiting value of 257 in the c direction and 111 in the a direction. $\epsilon(300°K) = 170$ and 86, respectively, and $\epsilon(1000°K) = 97$ and 58. Calculations of the Lorentz correction which take into account the actual geometry of the lattice were made by the method described by Slater[1] and Cohen.[2] The calculated local fields at the lattice sites are not very different from what would be expected if all the sites had cubic environments. The values calculated for the electronic and ionic polarizabilities are similar to values used by Slater[1] and Triebwasser[3] to explain the dielectric constant of $BaTiO_3$.

[1] J. C. Slater, Phys. Rev. 78, 748 (1950).
[2] M. H. Cohen, Phys. Rev. 84, 368 (1951).
[3] S. Triebwasser, J. Phys. Chem. 3, 53 (1957).

VA6. Dielectric Breakdown in O_2 for 3-cm Waves as a Function of Flow.* JAMES J. BRADY AND JOHN G. SKINNER, *Oregon State College.*—Pulsed power from a 3-cm magnetron is sent through a section of constricted waveguide with a minimum gap distance of 1 mm. Oxygen gas at pressures between 5–12 mm Hg flows past the constriction. The rate of flow and pressure are separately controlled. A directional coupler in the line makes it possible to detect power reflected from a microwave discharge at the constriction. The transmitted power through the discharge region can also be measured. With the power below that needed for a discharge a small reflection from the constriction can be detected on an oscilloscope. When the power is sufficient to produce breakdown a sudden increase in the reflected signal is noted. With a reduction in power level a time delay between the beginning of the small reflection from the constriction and the large reflection from the discharge can be measured. With sufficient reduction in power the delay time approaches the length of the microwave pulse (1μsec). With constant power, but increasing gas flow velocity (up to 10^4 cm/sec) the delay time increases. Curves showing the delay time as a function of velocity will be presented.

* This work is supported by the Physics Technology Department of the Boeing Airplane Company.

VA7. Crystal Radii for the Alkali and Halogen Ions in the Alkali Halides. FAUSTO FUMI AND MARIO TOSI,* *Universita di Pavia, Italy.*—The Huggins-Mayer formulation of the Born model of ionic solids is shown to permit the complete determination from solid-state data of a set of crystal radii for the alkali and halogen ions in the various alkali halides. The procedure eliminates the assumptions on the size of a particular ion, or on the relative sizes of isoelectronic alkali and halogen ions, intrinsic to the traditional empirical sets of crystal radii. The crystal radii for the alkali ions obtained in this way are larger than the traditional radii by one or two tenths of an angstrom, and the crystal radii for the halogen ions are correspondingly smaller. In particular, the crystal radii for the Na^+ and Cl^- ions in NaCl agree with those deduced by Witte[1] from the electron map of the crystal within their expected accuracy.

* Present address: Solid State Science Division, Argonne National Laboratory, Argonne, Illinois.
[1] H. Witte and E. Wölfel, Z. Physik. Chem. 3, 296 (1955).

VA8. On the Polymorphic Transitions of the Alkali Halides. MARIO TOSI AND FAUSTO FUMI,* *Universita di Pavia, Italy.*—The Born model of ionic solids is shown to account for the relative stability of the NaCl and CsCl phases of an alkali halide crystal, and to provide, in particular, values for the work involved in the pressure transitions of the potassium and rubidium halides from the NaCl to the CsCl phase in quantitative agreement with experiment, if one allows for the dependence of the overlap repulsive parameters from the crystal structure. The physical significance of this dependence will be discussed.

* Present address: Solid State Science Division, Argonne National Laboratory.

THURSDAY AFTERNOON AT 2:00

Terrace Room, Mark Thomas Inn

(W. O. STATTON presiding)

High-Polymer Physics. VI

Invited Papers

W1. Crystallization Mechanisms in Polymers. L. MANDELKERN, *National Bureau of Standards.* (40 min.)

W2. Theory of Chain Folding in Bulk Crystallization. J. D. HOFFMAN, *National Bureau of Standards.* (40 min.)

Contributed Papers

W3. Morphology of Polyhexamethylene Adipamide Crystals. F. KHOURY, *American Viscose Corporation* (introduced by D. W. McCall).—66-nylon has been crystallized by exposing solutions of the polymer in 90% formic acid to air at 100% R.H. Lamellar crystals and branched sheaves were formed. The former consist predominantly of very long narrow basal platelets (50–100 A thick) possessing a distinct direction of rapid growth. Of the two crystal edges parallel to the latter direction, one is invariably smooth (I), whereas the other (II) exhibits considerable reentrance. Overlapping growth steps

(III) (50–100 A thick) initiated near (I) and oriented at ~65° to it are always observed in these crystals. (III) extend to varying degrees across the width of the crystal and their lateral edges are parallel to (I) and (II). From electron diffraction it is found that the (100) crystal planes are parallel to (III) and perpendicular to the surface of the lamellas. Hence the hydrogen bonds are parallel to the direction of rapid growth. There is evidence based on some diffraction patterns that the (010) planes are parallel to (I) and that the chain molecules are probably preferentially normal to the lamellas. In view of the frequent absence of all reflections except the (100) this latter deduction is still tentative. Twinning and folding of twinned crystals are discussed. The sheaf branches exhibit a habit similar to that of the single crystals.

W4. X-ray Studies of Quenched, Drawn, and Annealed Polypropylene. HAROLD W. WYCKOFF, *American Viscose Corporation.*—Cold drawing of quenched polypropylene film is shown to break up the existing crystallites yielding a well oriented paracrystalline starting material for annealing studies. The same trend exists when the film is annealed before drawing and in this case the paracrystalline moiety is better oriented than the crystalline component except after extreme draw. Isometric annealing at various temperatures followed by detailed x-ray studies demonstrate the usefulness of the three phase model in such situations. There is an unorientable amorphous phase (presumably atactic polymer), the orientable paracrystalline phase with liquid like lateral order and the orientable highly ordered crystalline phase. Data on the temperature dependence of the conversion from paracrystal to crystal and on the recrystallization from small strained crystals to larger more perfect crystals have been obtained. In the latter case intensities down to 1% of the peak height have been quantitatively accounted for. An approximation formula for the line shape expected from cylindrical crystallites in a fiber orientation have been derived and employed. These studies have been correlated with shrinkage studies, mechanical test results, and differential thermal analysis results. The small-angle x-ray scatter is correlated with visual whiteness and both result from laminar voids produced in drawing.

W5. Lamellar Crystallization in Low Density Polyethylene. P. H. GEIL, *du Pont Experimental Station.*—Low-density polyethylene crystallizes from the melt and from solution in the form of lamellae resembling those previously observed in higher density polyethylene. These lamellas (and spherulites composed of lamellas) are less perfect than those observed in higher density polyethylene. The short chain branches on the polyethylene molecules are included within the lamellas creating numerous defects and lowering the apparent crystallinity of the sample.

W6. Molecular Motion in Disordered Regions of Solid Polyethylene. W. P. SLICHTER, *Bell Telephone Laboratories, Inc.*—Recent observations by many workers of the morphology of polymer solids have led to comparisons of the ordered regions produced by different modes of crystallization. The nature and extent of disordered regions in such solids are also of major importance, although less readily examined than the ordered regions. Some comparisons of disordered regions are reported here, based on studies of nuclear magnetic relaxation times and line shapes in polymethylene and linear polyethylene. Comparisons are made among crystalline samples grown from dilute solution, solution-grown materials which have been heated, and samples which have been crystallized from the melt at various rates and given various annealing treatments. NMR measurements include a temperature range of 150°–400°K. The observed relaxation times are found to vary markedly with the mode of crystallization and the manner of heating, the distribution of relaxations being comparatively narrow for solution-grown samples and broad for certain melt-grown samples. The behavior is interpreted in terms of existing theories of the influence of the distribution of molecular motions upon NMR relaxations. Inferences are drawn as to differences in morphology of the disordered regions.

W7. Hypothesis of Voids in Semicrystalline Polymers. SHIRO MATSUOKA, *Bell Telephone Laboratories, Inc.*—The expression $\bar{V} = xV_c + (1-x)V_a$, for the specific volume of a semicrystalline polymer, is a highly successful approximation. x is the degree of crystallinity, V_c is the specific volume for the crystalline regions, and V_a is the specific volume for the amorphous regions. In specimens for which x is near unity this equation demands values for the parameters which are inconsistent with other experimental evaluations. We suggest that the discrepancy arises because of the presence of voids. Thus in addition to crystalline and noncrystalline regions we propose regions of zero density. The average volume of such voids is not known but their existence can be inferred from the significant, permanent density enhancement which can be brought about by pressure induced crystallization.

W8. Structure of *n*-Paraffins and *n*-Paraffin Mixtures and Their Relation to Some Linear Polymers. A. E. SMITH, *Shell Development Company.*—The addition of a few percent of neighboring homologs convert the even-numbered triclinic and monoclinic *n*-paraffins into an orthorhombic form which differs from the orthorhombic form *Pbcm* observed in pure odd *n*-paraffins. The slow separation of ordered stable phases of mixed *n*-paraffins of different composition ratios 1:1, 2:1, etc., were observed during a study of binary mixtures. The results for the *n*-paraffin mixtures can be explained in terms of difference in density of the pure triclinic, monoclinic and orthorhombic (odd) forms and those of the orthorhombic forms of the mixtures, and by the assumption that the ends of the chains in the mixtures tend to fold over the ends of the short chains, essentially in interstitial positions, to increase the van der Waals energy and stabilize this form relative to solid solutions of the triclinic and monoclinic forms. Single crystals of mixed *n*-paraffins with composition ratios of 1:1 and 2:1 were prepared and the detailed packing arrangement determined. The *C* dimensions of the unit cells are 137.2 and 202.0 A, respectively, for the 1:1 and 2:1 mixtures of $n\text{-}C_{34}H_{70}$ and $n\text{-}C_{28}H_{58}$. The occurrence of long spacings in drawn polyethylene fibers may have a different origin than the chain folding observed by Keller in single crystals of polyethylene and may be related to a separation of phases similar to that observed in *n*-paraffin mixtures.

W9. Crystallite Orientation and Spiral Structure of Cotton. LLOYD B. DELUCA AND ROLLIN S. ORR, *Southern Regional Research Laboratory.**—A method is demonstrated by which both crystallite orientation and spiral angle can be directly determined from the x-ray tracings of the 002 diffraction arc of combed bundles of cotton fibers. Balls has shown that cotton has a spiral structure and Sisson has shown, qualitatively, that these 022 arcs can be explained by applying two equal crystallite distributions separated by twice the spiral angle. If this distribution of crystallites is assumed to be a Gaussian distribution, the experimental arc can be generated theoretically. This method of analysis is applied to x-ray data for decrystallized and mercerized cottons. X-ray diffraction shows the effects of fine structure of after-treatments such as tension and boiling in water used on samples of slack amine-decrystallized and mercerized cotton yarns. The interdependence of the calculated parameters tc those of the gross arcs are given as well as the relationships of these quantities to the tensioning force which produced them.

* One of the laboratories of the Southern Utilization Research and Development Division, U. S. Department of Agriculture, Agricultural Research Service, New Orleans, Louisiana.

THURSDAY AFTERNOON AT 2:00

400 Spanagel Hall

(G. VINEYARD presiding)

Diffusion, Internal Friction

X1. Effect of Correlation on Anisotropic Diffusion.* J. G. MULLEN, *Argonne National Laboratory.*—The effect of Bardeen-Herring correlation on diffusion in anisotropic crystals is calculated by relating the mean square displacement of an atom after a time t to the atomic jump vectors. The primary effect of correlation is to scale the number of symmetrically equivalent jump vectors n_a, by a correlation factor f_a, with one correlation factor corresponding to each nonequivalent set of jump vectors. For anisotropic systems, each correlation factor will depend on more than one frequency factor, and each f will thus generally have a complicated temperature dependence even in the case of self-diffusion. Based on the data of Shirn, Wajda, and Huntington,[1] it is shown that a precise determination of the temperature dependence of the anisotropy of diffusion in zinc could be used to distinguish between the ring and vacancy mechanism of self-diffusion. A first-order calculation is made to show that the magnitude and temperature dependence of frequency factors inferred from anisotropic diffusion data can be significantly altered when the effect of correlation is included.

* Based on work performed under the auspices of the U. S. Atomic Energy Commission.
[1] G. Shirn, E. Wajda, and H. Huntington, Acta Met. 1, 513 (1953).

X2. Self-Diffusion in Ag-Zn System. C. T. TOMIZUKA, R. A. ROBERTS, AND R. H. DICKERSON, *University of Arizona.*—Comparison of the activation energies for internal friction and tracer diffusion in Ag-Zn and Cu-Zn system indicated that there is a difference (ΔE) of 3 to 4 kc between the results of the two methods of experiment.[1] Since the discrepancy in Ag-Zn was found in 31 at. % zinc, the measurement of ΔE as a function of Zn composition would supply information regarding the origin of each difference. The anelastic measurements of Novick[2] covers the Zn atomic percentage of 15 to 30, the measurement of tracer self-diffusion in 15 at. % Zn alloy. In order to facilitate the comparison of the results of diffusion of Ag and that of Zn, the mixture of Ag 111 (half-life 7.6 days) and Zn 65 (250 days) was used. Preliminary results indicate that such a method does not yield as accurate a measurement of diffusion coefficients as the normal method of diffusing a single type of tracer.

[1] D. Lazarus and C. T. Tomizuka, Phys. Rev. 103, 1155 (1956).
[2] A. Norwick, Phys. Rev. 88, 925 (1952).

X3. Diffusion of Tin In Tin-Indium Alloys.* E. KLOKHOLM,† *Franklin Institute Laboratories,* AND L. MULDAWER, *Temple University.*—The diffusion of tin in alloys of 1.83, 1.96, 2.10, 2.54, and 2.55 at. % indium was measured. Standard radioactive tracer techniques were used with Sn^{113} as the radioactive trace element. Diffusion temperatures were from 201° to 220°C with diffusion times of four to fourteen days. The diffusion data obtained showed a monotonic increase in diffusion rate with increasing indium content. Lee and Raynor[1] have reported the existence of excess vacancies in the composition region 1.85 to 2.4% indium. Some confirmation of their results was obtained from resistivity and lattice constant measurements. The diffusion alloys 1.96 and 2.10% In showed no unusual deviation in diffusion rate as compared to the diffusion rate expected in dilute alloys. The ratio of the diffusion rate perpendicular to that parallel to the "c" axis does, however, show an increase for the 1.96 and 2.10% In alloys. With the aid of a simplified vacancy diffusion model for the β-tin structure, it is possible to show that the increase in diffusion ratio D_a/D_c for 1.96 and 2.1% In alloys can be caused by a change in diffusion mechanism due to the presence of excess vacancies.

* This work was supported by the Atomic Energy Commission.
† Now at Research Department, Research and Development Division American Machine and Foundry Company.
[1] Lee and Raynor, Proc. Phys. Soc. (London) 67, 737 (1959).

X4. Kinetics of Thermal Diffusion in Dilute Alloys. R. E. HOWARD AND J. R. MANNING, *National Bureau of Standards.*—The effect of a temperature gradient on the diffusion of a dilute impurity in an fcc metal is considered. The impurities are assumed to diffuse by a vacancy mechanism. The impurity current, the mean displacement of an impurity atom, and the steady-state concentration gradient corresponding to zero current of impurities relative to the center of mass are calculated. Correlation effects and the effect of impurity-vacancy binding are included. The calculated expressions involve both the kinetic parameters that characterize isothermal impurity diffusion, and atomic "heats of transport," which describe the effect of a temperature gradient on atomic jump frequencies. It is shown that the heats of transport can be studied through measurements of the steady-state concentration gradient. In limiting cases of random association and of tight binding, data should be especially easy to interpret. The possibilities of another type of measurement, which studies the motion of a layer of tracer impurities, are also discussed.

X5. Vacancy Diffusion in Ge-doped GaAs. J. O. MCCALDIN, *Hughes Research Laboratories.*—The transfer of an atom between the two sublattices of a III-V compound is, in most cases, not likely. Consequently, in the bulk III-V compound without dislocations or grain boundaries, vacancies are confined to their respective sublattices, and diffusion should resemble that in an elemental semiconductor.[1] If, however, impurity atoms are allowed to transfer between sublattices, vacancies also transfer between sublattices and the diffusion processes are affected. The diffusion equation for this situation in nonlinear; however, solutions which can be obtained for special cases indicate that the effective diffusivity D of vacancies should vary inversely with the concentration N_t of the transferable impurity. Experiments were performed with a series of Ge-doped GaAs slices obtained from a p-type ingot described previously.[2] The slices were heated at 1100°C under 5 atm arsenic for four days to form an n-type layer. The depth of this layer varied some fivefold among the slices, being progressively shallower in slices toward the tail of the ingot. These results qualitatively confirm the inverse relationship expected for D and N_t; more quantitative measurements are now underway.

[1] B. Goldstein, Bull. Am. Phys. Soc. 5, 374 (1960).
[2] J. O. McCaldin and R. Harada, J. Appl. Phys. 31, 2065 (1960).

X6. Diffusion of Neon Isotopes in Fused Quartz. R. C. FRANK, D. E. SWETS, AND R. W. LEE, *General Motors Research Laboratories.*—The diffusion coefficients and permeabilities of Ne^{20} and Ne^{22} in fused quartz have been measured using a mass spectrometer as a detecting device. Three different fused quartz specimens were used and a total of nineteen measurements were made on each isotope in the temperature range of 440 to 980°C. For Ne^{20} the activation energy for diffusion was found to be 11 367±82 cal/g atom and the D_{o20} was

2.21×10^{-4} cm²/sec. Similarly for Ne^{22} the activation energy was $11\,340\pm130$ cal/g atom and the D_{o22} was 2.08×10^{-4} cm²/sec. The ratio of the D_o values is therefore $D_{o20}/D_{o22}=1.06$ and compares favorably with 1.049, the inverse square root of the mass relationship predicted by some diffusion theories. The solubilities were calculated by dividing the permeabilities by the diffusion coefficients. The heat of solution for Ne^{20} is -1950 ± 150 cal/g atom and S_{o20} is 5.59×10^{16} atoms/cc. The heat of solution for Ne^{22} is -1950 ± 170 cal/g atom and S_{o22} is 5.75×10^{16} atoms/cc. A rather thorough evaluation of the results obtained on the isotope effect will be presented.

X7. Effect of Internal Oxidation on the Residual Resistivity of Dilute Cu Alloys. S. T. SEKULA, *Oak Ridge National Laboratory.**—The decrease in electrical resistivity of a dilute copper alloy after a heat treatment in an oxygen atmosphere at a pressure of ~20 μ Hg is qualitatively understood as being due to the preferential oxidation and precipitation of solute atoms.[1,2] Thus, the residual resistivity of an alloy of 0.1 at. % iron in copper was initially 1.0×10^{-6} ohm-cm, and upon annealing at 750°C in 20-μ Hg pressure of oxygen the residual resistivity decreased by a factor of 200. The well-known resistance minimum due to iron in copper was also observed to disappear. The minimum and resistivity could be restored by reheating in a reducing atmosphere. From a similar study of an alloy of 0.1 at. % nickel in copper it is inferred that the minimum observed is not due to nickel but to a trace impurity subsequently identified by radioactivation analysis as cobalt.

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.
[1] J. K. Redman, *et al.*, Bull. Am. Phys. Soc. **4**, 150 (1959).
[2] C. A. Domenicali and E. L. Christenson, J. Appl. Phys. **31**, 1730 (1960).

X8. Anelastic Measurement of Diffusion of Oxygen in Hafnium.* EDGARDO BISOGNI AND CHARLES WERT, *University of Illinois.*—The anelastic behavior of hafnium has been measured in the temperature region 25° to 700°C. Two regions of high damping were observed, one a distinct damping peak at about 475°C (for 1 cps), the other a region of constantly increasing damping starting at 500°C and increasing steadily with temperature to 700°C, where the measurements stopped. The first of these is identified as being caused by diffusion of oxygen (and possibly nitrogen) in hafnium. The second is believed to be grain boundary damping. These results are similar to those found for alloys of titanium and oxygen by Miller and by Weinig and Gupta. In the present investigation most attention was paid to the peak at 475°C. It is enhanced in magnitude by oxidizing treatments. It is also enhanced by nitriding treatments, but this may be caused by oxidation during the nitriding. The activation energy for the peak is 52 to 58 kcal/mole, close to that reported for diffusion of oxygen in hafnium. A model is proposed for the damping effect.

* Work supported jointly by U. S. Air Force Office of Scientific Research and Argentine Council of Scientific and Technical Investigations.

X9. Bordoni Internal Friction Peaks in Aluminum.* H. S. SACK AND A. SHIBATA, *Cornell University.*—The internal friction of Aluminum single crystals and polycrystalline samples was measured between 50 and 300°K, at 40 000 and approximately 4000 cps. With coldworking a broad peak appears at about 110°K which can be considered as a superposition of two peaks, each about 40° wide. Their relative heights, and their positions vary with the amount and kind of coldwork, partial annealing, etc. The position and general appearance is independent of strain amplitude. From a comparison of the peak temperatures at the two frequencies, an activation energy of 4.3 ± 0.5 kcal/mole can be derived which is the same for both peaks within the experimental error. The peak height is reduced by room temperature annealing. A 6 hr anneal at 200°C is not sufficient to make the peak disappear completely. The addition of Ag up to 0.5% has little influence on the peak, while doping with Mg decreases the peak height. This correlates with observations of the amplitude dependence at room temperature: "the breakaway stress" is little affected by Ag, but raised by Mg.

* This research was supported by the U. S. Atomic Energy Commission and the Advanced Research Projects Agency.

X10. Temperature and Strain Amplitude Dependence of Internal Friction Phenomena in Cold-Worked Mo and W.* R. H. CHAMBERS AND J. SCHULTZ, *General Atomic.*†—Strain-amplitude dependent internal friction, rigidity, and Young's modulus measurements of cold-worked, vacuum-melted, and floating-zone melted Mo and W specimens were made from 5° to 450°K. Measurements were performed from 20 000 to 80 000 cps and strains of 10^{-7} to 10^{-5} by longitudinal resonant bar and from 5 to 50 cps and strains of 10^{-5} to 10^{-4} by an ultrasensitive inverted torsion pendulum. Two major peaks in the internal friction vs temperature curves are found at 20 000 cps in Mo: the α peak at 120°K and the β peak at 400°K; the α peak of W is at ~170°K. The β peaks resemble the Bordoni peaks in fcc Cu in that the peak heights increase with increasing amounts of cold work, saturate for small amounts of cold work, and have a wide distribution of relaxation times. The β peaks differ from those found in Cu by annealing out at a much lower reduced temperature—300°C for Mo and 500°C for W; also the α peaks show a strong shift to lower temperatures with annealing at temperatures above 300°C for Mo. Simultaneous with the β peak annealing is an increase in the breakaway strain amplitude. This change in the amplitude dependence is interpreted to be due to the pinning of the dislocation relaxation oscillators responsible for the β peak.

* Supported by U. S. Atomic Energy Commission.
† John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic, Division of General Dynamics Corporation, San Diego, California.

X11. Internal Friction and Modulus Changes in Cold-Worked Iron Containing Carbon. J. C. SWARTZ, *United States Steel Corporation.*—Damping and modulus measurements on polycrystalline 99.9% iron wire were made with a torsion pendulum. Deformation was accomplished by twisting each specimen in the pendulum at temperatures from 80° to 450°K. The experiments show that the Köster and viscosity effects[1] are manifestations of the same effect and correlate with transient creep. For these effects the damping is approximately proportional to $(\nu e^{Q/kT})^{-0.2}$ where ν is the oscillation frequency, kT has its usual meaning, and Q equals to activation energy for transient creep. At low temperatures the damping is temperature and frequency independent. For specimens containing $\lesssim$10 at. ppm carbon the modulus defect and damping at low temperature decrease slightly upon Snoek atmosphere formation[2] and an order of magnitude during carbon segregation. The results can be compared with theories which assume the impurity atoms cause the major constraint on the dislocation motion.

[1] A. S. Nowick, J. Appl. Phys. **25**, 1129 (1954).
[2] G. Schoeck and A. Seeger, Acta Met. **7**, 469 (1959).

X12. Internal Friction of Neutron-Irradiated Iron-Carbon.* H. WAGENBLAST† AND A. C. DAMASK,‡ *Brookhaven National Laboratory.*—Iron containing approximately 0.01 wt. % carbon was irradiated in the BNL reactor at different times and temperatures, and the amount of carbon in solution was measured by torsion pendulum internal friction. Regardless of the extent of precipitation prior to irradiation, no increase of carbon in solution was observed. Subsequent annealing showed that the irradiation always accelerated the disappearance of carbon from solution by about three orders of magnitude over the thermal rate. The extent of the accelerated decay of the internal friction peak is a function of irradiation time after 12 days irradiation the peak decays to background level.

As a function of total aging time, whether during or post reactor irradiation, all data fall on the same curve independently of irradiation after a 4-hr irradiation time. The decay curves are all second-order with an activation energy of the diffusion of carbon in iron in disagreement with the reaction and activation energy for thermal precipitation. Interpretations by enhanced nucleation and carbon-defect interaction are suggested.

* Supported in part by the U. S. Atomic Energy Commission.
† Guest Scientist from U. S. Steel Corporation.
‡ Guest Scientist from Frankford Arsenal.

X13. Effect of Boron on the Relaxation Spectrum of High-Purity Iron. J. D. WOLF AND J. E. HANLON, *E. I. du Pont de Nemours and Company, Inc.*, AND T. J. HOVICK, *Pennsylvania State University.*—There has long been a question whether boron enters into interstitial solid solution in body-centered cubic iron. To resolve this question, we compared the relaxation spectrum of a high-purity, zone-refined iron with that of a similar specimen into which boron had been introduced. Zone-refined iron was used in order to eliminate the interaction of boron and substitutional impurities, and to determine the effect of purity on the internal friction spectrum of iron. The spectrum of the zone-refined specimen, after wet hydrogen annealing, showed that the trace interstitial impurity level was below 1 ppm, so the possibility of boron interaction with interstitial impurities was minimized. The boron was then introduced and the relaxation spectrum measured. The data were analyzed to determine whether or not a stress-induced ordering peak exists for boron. All measurements were made with a torsion pendulum over a temperature range from $-160°$ to $+100°$C.

X14. Zener Relaxation in Iron-Rich Fe-Al Alloys. D. B. FISCHBACH, *Jet Propulsion Laboratory,* CIT.*—The Zener stress-induced ordering relaxation in Fe-Al alloys containing 8–36 at. % Al has been studied by both damping and elastic after effect techniques. A torsion pendulum apparatus was used and magnetic damping contributions were eliminated by making measurements in a 400-oe field. The damping peak occurs in the range $500°-550°$C at 1 cps. The results differ somewhat from those of Shyne and Sinnott.[1] The relaxation strength, Δ_G, does not follow the usual dependence on the square of the solute concentration, being too low at low concentrations and falling off above about 22 at. % Al. The behavior at low Al contents is attributed to short range ordering, whereas the decrease at high Al contents results from long range ordering. The effect of long range ordering is also apparent in the temperature dependence of Δ_G. The relaxation activation energy ΔH decreases with increasing Al content. At 17 at. % Al, $\Delta H = 56$ kcal/mole and $\log_{10} \tau_0 \simeq -16.0$.

* A contract facility of the National Aeronautics and Space Administration.
[1] J. C. Shyne and M. J. Sinnott, Trans. Am. Inst. Mining and Met. Engrs. 218, 861 (1960).

THURSDAY AFTERNOON AT 2:00

Copper Cup Room, Herrmann Hall

(W. HARRISON presiding)

Thermal Studies

Invited Paper

Y1. Thermal Conductivity in Semiconductors at High Temperatures. B. ABELES, *RCA Laboratories, Princeton, N. J.* (30 min.)

Contributed Papers

Y2. Thermal Conductivity Measurements in Silicon from 30° to 425°C.* ROBERT G. MORRIS AND JEROME G. HUST, *South Dakota School of Mines and Technology.*—The thermal conductivity of two p-type silicon single crystals [acceptor concentration $\cong 6(10)^{14}$ and $3(10)^{15}$ cm^{-3}] has been measured from 30° to 425°C by means of a series comparative method. Thermocouples for measuring temperature gradients are placed in thermal and electrical contact with the 12-mm-diam $\times 8$ mm samples. Difference emf's are then measured directly with the Dauphinee comparator circuit. Contacts between samples and between samples, source, and sink are made with ceramic cement. Radiation error is reduced to about 1% by use of a radiation shield, use of thin samples with good thermal end contacts and small gradients, and use of the Armco iron comparison standards both above and below the unknown. The thermal conductivity is 0.30 ± 0.04 cal/cm sec C° at 30°C and decreases nearly linearly with T^{-1} to 0.011 ± 0.02 cal/cm sec C° at 425°C, with the uncertainties shown due mostly to measurement of thermocouple separation. The thermal conductivity may be understood in terms of lattice conductivity alone to 425°C.

* This work supported in part by Office of Naval Research.

Y3. Thermal Diffusivity of Silicon at High Temperatures.* H. R. SHANKS, P. D. MAYCOCK, P. H. SIDLES, AND G. C. DANIELSON, *Institute for Atomic Research and Iowa State University.*—The thermal diffusivity of silicon from 25° to 1000°C has been measured by means of the technique developed by Kennedy,[1] who applied the method successfully to armco iron. Each silicon sample was in the form of a short round rod, surrounded by a cylindrical silicon guard; three thermocouples were attached at equally spaced intervals along the rod. The temperature of the two outer thermocouples determined the boundary conditions for the heat-flow equation. The temperature at the center thermocouple was calculated with a high speed computer for various values of thermal diffusivity, and the calculated temperature compared with the observed temperature to obtain the best value of thermal diffusivity at the ambient temeprature. The thermal diffusivity of silicons decreased from about 0.6 cm^2/sec at 100°C to 0.1 cm^2/sec at 1000°C. Our results are in general agreement with those of Abeles *et al.*,[2] who have reported data below 750°C.

* Contribution No. 989. Work was performed in the Ames Laboratory of the U. S. Atomic Energy Commission.
[1] W. L. Kennedy, U. S. Atomic Energy Commission Rept. IS-137, Iowa State University, Ames, Iowa (June, 1960).
[2] B. Abeles *et al.*, Thermoelectric Materials for Power Conversion, RCA Laboratories Progr. Rept. 6, Princeton, New Jersey (August, 1960).

Y4. Effect of Uniaxial Stress on the Thermal Conductivity of Germanium between 1.4° and 4.1°K. R. J. SLADEK,* *Westinghouse Research Laboratories.*—According to the theory of Keyes[1] the scattering of phonons by low concentrations of donors in Ge at liquid-helium temperatures is due to the effect of strain on the energy of an electron in a hydrogenlike donor state. This theory has successfully accounted for experimental data[2] on Ge having $\lesssim 2\times10^{16}$ Sb or As atoms/cc in the absence of applied stress, the strain being that associated with the phonons. We have measured the thermal conductivity of pure Ge and of Ge having $\sim10^{16}$ Sb or As atoms/cc in the presence of applied tensional stresses up to 2.9×10^{8} d/cm^2 as well as with no applied stress. Under the influence of the applied stress the thermal conductivity can be increased by up to a factor of 3 in Sb-doped samples while it remains unchanged in pure Ge or As-doped Ge. This behavior of As-doped Ge, as well as its zero stress thermal conductivity, is in accord with the large chemical shift in As ground state donor levels. Analysis of the excess in the thermal resistance of Sb-doped samples over that of pure Ge as a function of stress will be presented.

* Present address: Purdue University, Lafayette, Indiana.
[1] R. W. Keyes (unpublished).
[2] J. F. Goff and N. Pearlman, *Proceedings of the Seventh International Conference on Low Temperature Physics*, Toronto, 1960 (University of Toronto Press, Toronto, Canada, to be published).

Y5. Effect of Impurities on the Low-Temperature Thermal Conductivity of Silicon. M. G. HOLLAND, W. D. STRAUB, AND L. J. NEURINGER, *Raytheon Research Division.*—Thermal conductivity (4° to 300°K) and Hall effect and electrical resistivity (25° to 370°K) measurements have been made on samples of floating-zone silicon containing various concentrations of boron and phosphorus ranging from 10^{13}/cc to 10^{18}/cc. The Hall effect and resistivity data is used to determine the impurity concentrations. The small decrease in thermal conductivity of the phosphorus-doped silicon as the concentration is increased from 4×10^{13} to 1×10^{15} P/cc is consistent with the expected "mass difference" scattering. The decrease in thermal conductivity of boron-doped silicon as the concentration is increased from 1×10^{13} to 4×10^{15} B/cc is much greater than expected from "mass-difference" scattering alone. For the boron-doped samples, the thermal conductivity is greatly reduced at temperatures below the maximum, 26°K; that is, for two samples which differ by 20% at the conductivity maximum there is a factor of 2 difference at 10°K. As the impurity concentrations are increased to $\sim5\times10^{17}$ B/cc and $\sim10^{16}$ P/cc, the low temperature decrease is seen with both types of impurity, but it is more severe for the boron-doped samples. The effect in the phosphorus-doped samples may be due to compensating boron (or other group III) impurities but the analysis which yields the compensation at high impurity concentrations is not considered conclusive.

Y6. High-Temperature Thermal Conductivity Measurement. GLEN CHENEY AND MELVIN CUTLER, *General Atomic.**† —The small area contact method[1] has been adapted for measurement of thermal conductivity of electrical conduction at very high temperatures. The sample consists effectively of a rod which has a small constricted region near the center. A large current passed through the sample causes Joule heating in the constricted region. The local temperature rise causes a change in resistance δR which is observed as a transient when the current is turned on. The theory of the small area contact method shows that δR does not depend on the geometry, and is given by $1/12\ (\sigma/\kappa)(dR/dT)V^2$, where V is the voltage causing the heating, σ is the electrical conductivity, and dR/dT is the coefficient of the resistance change when the oven temperature is changed. Radiation effects are negligible if the constricted region is small enough (less than 1 mm). The method has been applied to measurements of several refractory metals (Ta, Mo, Pt) at temperatures as high as 1200°C. The experimental results for σ,κ and the Lorentz ration show reasonable agreement with previous data where they exist.

* Supported in part by the U. S. Atomic Energy Commission.
† John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic Division of General Dynamics Corporation, San Diego, California.
[1] M. Cutler, Bull. Am. Phys. Soc. Ser. II, 5, 281 (1960).

Y7. Method of Measuring Thermal Conductivity with No Radiation Errors.* W. D. BRENNAN AND J. K. RANEY, *Armour Research Foundation.*—A method of measuring thermal conductivity in the steady state originally developed by Barratt and Winter[1] has been modified for use at high temperatures in such a way as to eliminate errors due to radiative heat losses from the specimen. Measurements have been made on sintered SiC, MgF_2, and ZnS from room temperature up to about 500°C and apparently the technique can be extended to considerably higher temperatures. The temperature dependence of all three materials was approximately $1/T$ over the measured range. The measurement also yields the total emissivity and for MgF_2 and ZnS the emissivity as measured by this method was in good agreement with optical measurements. An important advantage of this method of measuring thermal conductivity, apart from the elimination of errors due to radiative losses, is that a series of measurements at different temperatures can be made relatively rapidly; as many as four measurements can be made in one day.

* This work was done under the auspices of the Air Research and Development Command, U. S. Air Force.
[1] T. Barratt and R. M. Winter, Phil. Mag. 49, 313 (1924).

Y8. Apparatus for Rapid Measurement of Thermal Conductivity. JOHN STAMPER AND MAX BRYANT, *Texas Instruments Inc.*—An apparatus is described for making measurements of thermal conductivity of solids in the range 10^{-1}W/cm °C and below. An absolute steady-state method is employed with the heater and sink maintained at room temperature and the ice point, respectively. The temperature of the heater is closely matched to that of a massive brass guard ring surrounding it. Flat isotherms established normal to the sample axis by providing a low thermal conductance path between the heater-guard assembly and the heat sink, allow accurate measurements to be made in air. Sample contacts are made by applying axial pressure or by soldering to copper discs which fit into the heater and sink. Samples with cross sections up to that of the heater may be accommodated. Power loss from the exposed area of the heater can be calculated from experimentally determined parameters. Rapid measurements are possible since the heater and sink are maintained at fixed temperatures throughout the measurement. An analysis of power losses indicates an accuracy of ±5%. Experiments on fused quartz substantiate this accuracy. Use of the method at other temperatures is discussed.

Y9. Technique for Studying Temperature Gradient Effects on Marker Movement in Noble Metals.* C. J. MEECHAN, *Atomics International.*—A technique has been developed which enables one to measure a relative marker movement of a few microns in specimens suitable for experiments in a temperature gradient of the order of 2000°C/cm. Fused quartz fibers, 10–20 μ in diameter, are sandwiched between cylindrical, micropolished layers of the metal to be studied. These sandwiches are sintered under pressure in a special jig near the melting point of the metal, after which they are machined to a toadstool shape for the temperature gradient experiment. The mounting jig is designed such that it is possible to position the fibers within 30 μ of the specimen centerline and parallel to one another within 8 μ over a 5 mm length. By making initial measurements at both sides of the specimen where the fibers protrude, it is possible to detect relative movement between two fibers with a precision of about ±3 μ. Preliminary results

on marker movement in gold in temperature gradients of the order of 1700°C/cm will be discussed.

* This work supported by U. S. Atomic Energy Commission.

Y10. Current Induced Marker Motion in Platinum Wires.* THEODOR HEHENKAMP AND PAUL S. C. HO, *Rensselaer Polytechnic Institute* (introduced by H. B. Huntington).—Measurements of marker motion in platinum, by a technique previously used by Huntington and Grone,[1] have been made from 1350° to 1730°C. At low temperature the markers move toward the cathode but above 1600°C reverse and move toward the anode, a behavior which resembles that of copper. The phenomenon partially fits a model given by Huntington. The accuracy of the present temperature measurements was improved by means of a pyrometer consisting of a light-sensitive resistor on which a small area of the wire can be sharply focused. The resistor is mounted in a measuring microscope which is used to determine the marker positions. By translating the micrometer slide the temperature distribution down the wire can be determined for temperatures above 900°C.

* Supported by the U. S. Atomic Energy Commission.
[1] H. B. Huntington and A. R. Grone, Bull. Am. Phys. Soc. 4, 172 (1959).

Y11. Specific Heats of Delta-Phase ZrH and ZrD.* WALTER J. TOMASCH, *Atomics International*.—The specific heats of $ZrH_{1.88}$ and $ZrD_{1.88}$ have been measured in the temperature interval 30°–500°C. These data are interpreted in terms of an Einstein oscillator model for the hydrogen and deuterium specific heat contributions. This model is in accord with earlier inelastic neutron scattering studies,[1] and features an isotopic depression of the deuteride Einstein temperature by a factor $1/\sqrt{2}$ relative to the hydride value. Over the interval 30°–200°C, the data are in quantitative agreement with predictions. At higher temperatures, the deuteride specific heat is smaller than anticipated, by as much as twelve per cent of the predicted deuterium contribution. Possible origins for these deviations will be discussed. The hydride Einstein temperature calculated from the difference between deuteride and hydride specific heats at 150°C is 1500°±300°K, as compared with the inelastic neutron scattering value of 1500°±60°K.

* Supported by the U. S. Atomic Energy Commission.
[1] I. Pelah, C. M. Eisenhauer, D. J. Hughes, and H. Palevsky, Phys. Rev. 108, 1091 (1957); A. Andresen, A. W. McReynolds, M. Nelkin, M. Rosenbluth, and W. Whittemore, *ibid.*, 108, 1092 (1957); W. L. Whittemore and A. W. McReynolds, *ibid.*, 113, 806 (1959).

THURSDAY AFTERNOON AT 2:00

421 Spanagel Hall

(G. D. WATKINS presiding)

Irradiation Effects

Invited Paper

Z1. Intrinsic Radiation Defects in Silicon. G. D. WATKINS, *General Electric Laboratory, Schenectady.* (30 min.)

Contributed Papers

Z2. Irradiation Effects on Thermal Decompositions.* JOSEPH JACH,† *Brookhaven National Laboratory* (introduced by G. J. Dienes).—A brief review is given of the effects of neutron and gamma-ray irradiations on the thermal decomposition of ionic solids. Some recent work on the thermal decomposition kinetics of sodium bromate is reported. The reaction is $NaBrO_3 \rightarrow NaBr + \frac{3}{2} O_2$. Over most of the temperature range studied (320°–430°C), decomposition curves (pressure vs time) can be represented by the classical cube law fit, i.e., $p = at^3 + bt^2 + ct$, but marked changes in kinetics occur at lower temperatures. Neutron and gamma-ray irradiations prior to the thermal decomposition increase the reaction rates and change the kinetic forms and these results are discussed in terms of current ideas of solid-state physics.

* Work performed primarily at Brookhaven National Laboratory and supported jointly by Picatinny Arsenal and the U. S. Atomic Energy Commission.
† Guest Scientist, Brookhaven National Laboratory, Upton, New York.

Z3. Energy Loss of Moving Charged Particle in a Valence or Ionic Crystal. H. C. SCHWEINLER, *Oak Ridge National Laboratory.**—A theoretical calculation is presented for the energy loss through hole-electron pair formation of a massive charged particle moving through a valence or ionic crystal. The process has a threshold (proton energy 125 ev for Si, ~10 kev for NaCl), and the calculation is best for particle energies not far above threshold. Considering the valence and conduction bands, one is taken to be spherical and the other may be several ellipsoids of revolution (possibly off-center in reciprocal space). The minimum energy loss per hole-electron pair is 1.19 ev in Si; this energy loss, and the threshold energy, vary with the direction of motion of the particles relative to the coordinate axes of the crystal. This theory suggests that semiconductor materials suitable for charged-particle detectors will not only have a small energy gap, but also have at least one energy surface consisting of ellipsoids which are rather far off-center in reciprocal space.

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

Z4. Interpretation of Electron Irradiation Damage Recovery in InSb.* F. H. EISEN, *Atomics International*—The recovery of electron irradiation damage in *n*-type InSb occurs in five well-defined stages. There is evidence that the recovery in stages I and II (numbered in order of increasing temperature) tends to restore the pre-irradiation condition of the sample by recombination of close interstitial-vacancy pairs without the formation of defect-impurity complexes. At first glance, it would seem these stages should obey first order kinetics. However, it is observed that the exact recovery temperature, kinetics, and activation energy depend on the initial electron concentration. This suggests that the recovery may depend on the position of the Fermi level, and this effect may help explain the deviation from first order kinetics which occurs in these stages. A model in which ionized defects have a lower activation energy for recovery and recover by a first order process has been investigated. The predicted deviation from first order kinetics is not great enough to fit the data. This suggests the assumption of first order recovery for the ionized

defects should be modified, perhaps by allowing a process in which more than one jump is rate determining.

* Supported by the U. S. Atomic Energy Commission.

Z5. Annealing of Electron-Irradiated GaAs.* L. W. AUKERMAN, P. C. PETERS,† AND R. D. GRAFT, *Battelle Memorial Institute.*—Annealing experiments following 1-Mev electron bombardments which decreased the carrier concentration of the GaAs specimens by no more than 20% indicate a brief transient followed by a monomolecular recovery. The decay constant for the monomolecular region obeys the relationship

$$\lambda(T)=\lambda(T_0)\exp\frac{E}{k}\left[\frac{1}{T_0}-\frac{1}{T}\right], \quad T_0=483°\text{K}.$$

For all specimens E lies within experimental error of 1.9 ev; but $\lambda(T_0)$ differs by as much as two orders of magnitude for different samples. This suggests that the recovery is sensitive to impurities or dislocations. The electron damage appears to recover completely in a single stage at about 210°C. This contrasts interestingly with the annealing of neutron damage which recovers only partially during two stages centered at about 210° and 430°C, respectively.[1]

* Supported by the Aeronautical Research Laboratory, Wright Air Development Division.
† Presently at California Institute of Technology.
[1] L. W. Aukerman, *et al.*, Bull. Am. Phys. Soc. 5, 167 (1960).

Z6. High Dose Rate Annealing Kinetics in Ge.* JEROME ROTHSTEIN, *Edgerton Germeshausen and Grier, Inc.*—Previous results on annealing kinetics in I_{∞} on Ge transistors in pulsed nuclear environments yielding two relaxation times (100 μsec, Godiva; 10 msec, Triga) were extended to intermediate times and dose rates at the KEWB reactor. No new relaxation times were found, but at the highest doses and peak dose rates an effect was discovered which suggests radiation annealing and/or annealing kinetics of order higher than one. The effect was a narrowing of the normalized I_{∞} pulse on the trailing side, relative to the normalized dose rate curve. The relaxation tail later crossed the dose rate curve and decayed with a time constant compatible with Triga results. As ordinary relaxation could only broaden, not narrow, the I_{∞} response, new mechanisms must be involved, thought to be either or both of the two mentioned. A tentative theory depending both on instantaneous dose and integrated damage simultaneously will be briefly described.

* Work supported by the U. S. Army Research and Development Laboratories under contract.

Z7. Thermal Neutron Induced Recoil and Transmutation Effects in Isotopic Ge^{74}. J. W. CLELAND AND J. H. CRAWFORD, JR., *Oak Ridge National Laboratory.**—The average kinetic energy of recoil of the various isotopes of Ge and Si following an (n,γ) process is much greater than the threshold displacement energy; however, multiple defect production has not been observed.[1] Recent experiments utilizing 96% isotopically enriched Ge^{74} material[2] indicate that the initial donor concentration is not appreciably altered by thermal neutron irradiation; however, subsequent annealing increases the apparent donor concentration to that expected from the resulting As^{75}. Since approximately 6 Frenkel pairs per recoiling Ge^{74} are expected from simple displacement theory, these results suggest that much of the recoil energy is used in (1) forming unstable defects or (2) replacement collisions and lattice excitations, with the recoil normally remaining substitutional and the displacement of a neighboring atom occurring with less than unit efficiency. The same considerations could also apply to previous results on normal isotopic material.

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.
[1] J. H. Crawford, Jr., and J. W. Cleland, IAEA Conference on Radioisotopes, Copenhagen, 1960 (to be published).
[2] We are indebted to W. Brown, T. Geballe, and associates of the Bell Telephone Laboratories for this material.

Z8. Reordering Processes in Neutron Irradiated *p*-Type Germanium. H. J. STEIN, *Sandia Laboratory.*—The conductivity, Hall coefficient and photoconductivity of indium-doped (6×10^{14}/cm³) Ge have been measured as a function of time at a stable temperature, following irradiation with a pulse of neutrons from the Godiva II assembly.[1] The initial changes in conductivity and the nature of subsequent reordering are markedly dependent on temperature. At 73° and 300°K the initial values for $dP/d\phi$ are -3 and $+1.5$/neutron-cm, respectively, and the values for $(d\mu/\mu_0)/d\phi$ are -2.4×10^{-15} and $\langle-10^{-16}$/ neutron-cm^{-2}, respectively. The conductivity was stable following irradiation at 73°K. At higher temperatures, two predominant reordering processes (A and B) were noted. Both were observed at 150°K, where A dominated for 100 sec, and then B became dominant. The hole concentration and mobility were decreased by A, but increased by B. B exhibited kinetics of nearly the second order with an activation energy of 0.3 ev. This could be reduced to 0.2 ev by illuminating the sample. At 200° K, B changed the net $dP/d\phi$ from -1.7 to $+0.8$/ neutron-cm. B also caused a recovery of nearly 50% in photoconductivity.

[1] H. J. Stein, J. Appl. Phys. 31, 1309 (1960).

Z9. Defect Introduction in Tellurium by Electrons with Energies between 4 and 25 Mev. E. G. WIKNER, J. H. HARRITY, AND V. A. J. VAN LINT, *General Atomic.**—Tellurium,[1] initial c-axis conductivity 0.036 ohm^{-1} cm^{-1} at 80°K, was irradiated at 80°K by electrons with energies of 4, 10, and 25 Mev. The conductivity, Hall effect, and magnetoresistance were measured as a function of irradiation. The numbers of carriers introduced per unit flux at 4, 10, and 25 Mev are 2.7, 3.7, and 6.2, respectively. The Seitz-Koehler[2] theory predicts the ratio of the number of defects formed by 4- and 10-Mev electrons and by 4- and 25-Mev electrons to be 1.38 and 1.78, respectively. Assuming the number of carriers introduced per unit flux is a measure of the rate at which defects are introduced, we find experimentally that the ratio of defects formed between 4 and 10 Mev and between 4 and 25 Mev electrons to be 1.35 and 2.3. The difference between the theoretical and experimental 4 to 25 Mev ratio is much greater than the experimental uncertainty and can be ascribed to the production of defect clusters at the higher energy. One anomolous behavior observed is an initial increase in the Hall mobility with irradiation. No annealing is observed at 80°K but a very fast anneal region occurs at 100°K. The samples anneal completely if held at 85°C for 10 minutes.

* John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic Division of General Dynamics Corporation, San Diego, California.
[1] Supplied by G. D. Long, Honeywell Research Center.
[2] F. Seitz and J. S. Koehler, *Solid-State Physics* (Academic Press, Inc., New York), Vol. 2, p. 307.

Z10. Magneto-Optic Studies on Radiation-Darkened Cerium Glass. PERRY B. ALERS, *U. S. Naval Research Laboratory, Washington, D. C.*—Monk[1] found that the addition of cerium to glass tended to inhibit the darkening experienced by the glass when exposed to prolonged gamma radiation. He proposed a mechanism which involved a change in valence of the cerium. Subsequent work by Kreidl and Hensler,[2] however, using optical absorption curves, indicated that a simple change probably did not take place. Since substances containing cerous (Ce^{3+}) ion show strong paramagnetic Faraday rotations, while those containing ceric (Ce^{4+}) ion do not, the present series of experiments was undertaken in an attempt to detect a valence change magneto-optically. Using liquid helium temperatures and fields ranging to 70 kgauss, the Faraday effect in glass specimens containing large amounts of cerous metaphosphate was investigated subsequent to successive dosages of 10,[6] 10,[7] and 10^8 r using Co^{60} gammas. No measurable changes in rotation, and hence in the amount of Ce^{3+} present, were detected. Absorption curves taken before and after

irradiation, and also after annealing, will be compared with those reported by Kreidl and Hensler.

[1] G. S. Monk, Argonne National Lab. Rept. ANL-4536, (1950).
[2] N. J. Kreidl and J. R. Hensler, J. Am. Ceram. Soc. 38, 423 (1955).

Z11. Electron Spin Resonance in Neutron-Irradiated TiO_2 Single Crystals. R. A. WEEKS, *Oak Ridge National Laboratory.**—In rutile (TiO_2) single crystals, neutron irradiation produces paramagnetic centers whose spin resonance has been observed at ~300° and 78°K. The characteristics of the center can be described by a spin Hamiltonian in which $S=\frac{1}{2}$ and $g_x=1.935\pm0.003$, $g_z=1.989\pm0.003$, and $g_y\sim1.985$. The orientation of the g tensor is g_x approximately parallel to [110] and g_z approximately parallel to [001]. The number of lines observed for different orientations of the crystal with respect to the applied field suggest that the center is apparently related to the distorted octahedra around each Ti, the octahedra being rotated 90° with respect to adjacent Ti. The number of lines observed and their intensity ratios suggest that there are sixteen equivalent sites. This center is not the same as the one observed in reduced rutile.[1]

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.
[1] P. F. Chester, Bull. Am. Phys. Soc. 5, 73 (1960).

SUPPLEMENTARY PROGRAMME

SP1. Generalization of Benson's Calculation of Madelung Constants.* R. A. SACK,† *British Rayon Research Association, Manchester,* AND T. C. WADDINGTON, *University of Cambridge, England* (introduced by C. C. J. Roothaan).—If a spacial lattice of point charges with periods a_1, a_2, a_3 is subjected to an affine deformation which leaves a_1, a_3 and the angles between the axes constant, the derivative $\partial V/\partial a_3$ of the potential at any point can be expressed as a double Fourier series with exponential coefficients. The corresponding series for V diverges, but V can be calculated by means of Euler's theorem $V=-\Sigma a_i\partial V/\partial a_i$. For NaCl-type lattices Benson's formula is obtained.[1,2] If some planes contain net charges, a limiting process must be applied. The series converge rapidly in most cases.

* To be called for at the end of Session QA if the Chairman rules that time permits.
† Present address: Laboratory of Molecular Structure and Spectra, University of Chicago.
[1] G. C. Benson, Can. J. Phys. 34, 888 (1956).
[2] T. C. Waddington, Trans. Faraday Soc. 56, 305 (1956).

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Flood, W. F.—NA1
Flygare, Willis H.—P10
Fourie, J. T.—U7
Frank, R. C.—X6
Fraser, D. B.—L3
Frazer, B. C.—VA3
Fredericks, W. J.—C11
Fredkin, D. R.—BA2
Freeman, A. J.—A7, UA10
Frey, D. A.—UA7
Friauf, R. J.—D11, IA8
Fritzsche, H.—KA1
Fromhold, A. T., Jr.—N11
Fumi, Fausto—VA7, VA8

Gall, W. G.—GA4
Galt, J. K.—N3
Garber, M.—N12
Garrett, C. G. B.—LA2
Geballe, T. H.—F10
Geil, P. H.—W5
Gendron, M. F.—F12
Gerson, Robert—L11
Geschwind, S.—E1, E2
Gibbs, P.—U6, U12
Gibson, J. B.—R10
Gilbert, J. F.—B4
Gill, Stanley J.—MA8
Gilliam, O. R.—E3, E4
Girifalco, L. A.—R11, R12
Glicksman, Maurice—DA2, DA11
Goetzberger, A.—B7
Goldsborough, J. P.—M5
Gonser, U.—K5
Goodkind, J.—O2
Goodman, Gordon L.—P8, UA11
Gordon, R. B.—D5, D6
Gornick, F.—JA1, PA1, PA2
Gossard, A. C.—A6
Goudsmit, S. A.—V1
Graft, R. D.—Z5
Gritton, G. V.—D11
Gwinn, William D.—P9, P10

Hager, Robert J.—I5
Hake, R. R.—N13
Hall, John J.—KA2
Halsted, R. E.—NA10
Hamilton, D. R.—NA11, V4
Hanak, J. J.—N14
Handler, P.—I6
Hanlon, J. E.—X13
Happe, James—A11
Harman, Theodore C.—QA6, QA7, QA8
Harrity, J. H.—Z9
Hartman, T. E.—B11
Haslett, James C.—I2
Hass, M.—K6
Hatchett, J. L.—C11
Hauser, J. J.—F15
Hayes, Robert G.—M6
Haynes, J. R.—NA1
Heeger, A. J.—S7
Hehenkamp, Theodor—Y10
Heinecke, W. J.—V9
Heller, G. S.—DA4
Henderson, James W.—S11
Henley, R.—B9
Henry, Warren E.—VA4
Hensel, J. C.—DA3
Herman, R.—OA3, Banquet
Herschbach, Dudley R.—P12
Hewitt, R. R.—A12
Ho, Paul S. C.—Y10
Hobart, Robert H.—U4
Hoffman, J. D.—W2
Hoffman, R. W.—FA11
Hofstadter, R.—OA3
Holcomb, D. F.—A2
Holland, M. G.—Y5
Hollander, Lewis E.—L6
Holmstron, Fred E.—V12
Holton, William C.—D1, D2
Honig, A.—E11
Honnold, Vincent R.—D10
Hopfield, John J.—BA6
Horwitz, Gerald—FA2, FA3
Houston, B. B., Jr.—KA3
Hovick, T. J.—X13
Howard, R. E.—X4
Hsiao, C. C.—JA6, JA7
Huber, R. J.—U6
Hudda, F. G.—V8
Hust, Jerome G.—Y2
Hutchison, C. A., Jr.—T1
Hutson, A. R.—C2
Huzinaga, S.—UA4

Jaccarino, V.—A6, A8, K8, K9
Jach, Joseph—Z2
Jaffe, Hans—L9
Jain, A. L.—J2
Jarrett, Howard J.—S1
Javan, A.—DA1
Jeffers, F.—E10
Jeffries, C. D.—M9
Joiner, William—F14
Jones, R. E.—F12
Jossem, E. L.—BA10
Judge, Jane—TA4

Kane, Evan O.—BA5
Kaplan, R.—D4
Kaplan, T. A.—CA1
Katz, E.—IA1
Katz, J.—UA14
Kauffman, J. W.—R7, R8
Kawai, Hiromichi—TA3
Keith, H. D.—PA3, PA4
Keller, Joseph M.—EA4
Keller, Keaton—OA1
Kelly, W. H.—K6
Kernohan, R. H.—R9
Kevorkian, Hagop K.—PA8
Khoury, F.—W3
Kikuchi, C.—E7
King, J. C.—L3, L4
Kinsey, James L.—P12
Klabunde, C. E.—HA5
Klauder, J. R.—A1, N2
Klein, Claude A.—HA3, HA4
Klein, Melvin P.—A11
Kleinman, Leonard—BA8
Klemens, Paul G.—G3
Klokholm, E.—X3
Knight, Robert D.—V12
Knight, W. D.—A9, F7
Knutson, Charles D.—D4
Koehler, J. S.—J4
Koenig, P.—NA5
Koenig, S. H.—KA2
Kohn, W.—H3
Kommandeur, Jan—IA2
Kovacs, A. J.—PA5
Krause, Sonja—MA9
Krebs, James J.—M3
Krimm, S.—PA9
Kroemer, H.—DA9
Krogstad, R. S.—KA7
Kulp, Bernard A.—C6
Kunzler, J. E.—N2
Kuper, C. G.—F2
Kwei, George H.—P12
La Force, Richard Conley—FA9
Landau, L.—P13
Landwehr, G.—I6
Lane, G. T.—O3
Langenberg, D. N.—DA5, F6
Langenecker, B.—U13
Langer, D. W.—C7
Larsen, R. E.—R4
Larson, O. W.—C8
Lasher, G. J.—EA9
Laskar, A. L.—IA7
Laurie, Victor W.—P7
Lauterbach, W. R.—C7
Lauttman, R. G.—MA1, MA2
Lawrence, Wallace C.—JA3
Lax, B.—B1
Lax, Melvin—BA6, BA7, NA1
Lazarus, David—G4
Lee, R. W.—X6
Legrand, Donald G.—GA3
Leivo, William J.—M12
Leslie, D. H.—N13
Levinstein, H.—QA10
Levy, Paul W.—D13, E3, E4
Lewis, W. B.—D11
Lieberman, David—R1
Lindenmeyer, Paul H.—JA3
Linderberg, Jan—UA12
Lindgren, W. A.—B15
Lipscomb, William N.—UA8
Litton, C. W.—C9, C10
Logan, R. A.—B4, QA4
Loh, E.—NA9
Loh, W. H. T.—EA13
Lorenz, M.—NA10
Love, W. F.—I2
Low, W.—M1
Ludwig, G. W.—E12, E13
Lurio, Allen—M11
Lynch, D. W.—NA5

Macek, R. J.—V7
Mahr, Herbert—D14
Maker, Paul D.—DA8
Makhov, G.—E8, E9
Mandel, M.—M5
Mandelkern, L.—PA1, PA2, PA6, W1
Manning, J. R.—X4
Maradudin, A. A.—EA5, EA6, EA7
Marcus, J. A.—N4
Marple, D. T. F.—NA10
Martin, G. M.—PA6
Mason, D.—E7
Masuda, Y.—F8
Masumi, Taizo—IA6
Matsuoka, Shiro—W7
Mattes, Brenton L.—L6
Matthias, B. T.—A5, F10, LA1
Maycock, P. D.—Y3
Mayer, James W.—B13, B14
Mayer, S. W.—UA14
McCaldin, J. O.—X5
McCall, David W.—JA4
McConville, G. T.—N14
McCrum, N. G.—GA4
McDermott, M. N.—M10
McDonald, B.—B8
McKinney, John E.—GA6
McLachlan, A. D.—T3
McLean, A. D.—UA3

Meechan, C. J.—Y9
Meisenheimer, R. G.—VA2
Melamed, Nathan T.—C12
Mendelson, Sol—U5
Menefee, Emory—TA7, TA8
Mengali, O. J.—B15
Mercereau, J. E.—F3
Merritt, F. R.—N3
Meshii, M.—R8
Meyer, H.—CA4
Meyer, M.—U3
Meyerhofer, D.—KA11
Michel, R. E.—DA6, DA7
Miles, John L.—F5
Milford, Frederick J.—N9
Mizushima, M.—UA7
Moore, Emmett B., Jr.—UA8
Moore, R. L.—QA5
Morgan, L. O.—M7
Morgan, Thomas N.—KA10
Mori, T.—R8
Morris, Donald E.—F9
Morris, Robert G.—Y2
Morrison, S. Roy—B10
Moss, R. W.—KA7
Moszkowski, S. A.—OA2
Mozer, Bernard—K4
Muldawer, L.—S2, X3
Mullen, J. G.—X1
Muller, M. W.—FA13
Muray, Julius J.—IA9
Myers, Rollie J.—M6

Nagle, D. E.—K10
Narath, A.—P10
Nathan, Marshall I.—B5
Nettel, S. J.—N1
Neuringer, Leo J.—KA14, Y5
Newman, R.—NA9
Nezbeda, C. W.—HA2
Noer, Richard J.—F7
Nolle, A. W.—M7
Nolta, James P.—D10
Novick, R.—M10
Nowick, A. S.—IA4, IA5
Nussbaum, Allen—I5

Odajima, A.—JA5
Oliver, P. R.—R12
Onishi, T.—PA9
Orr, Rollin S.—W9
O'Sullivan, W. J.—A14

Padden, F. J., Jr.—PA3, PA4
Pake, G. E.—M5, T4
Palmer, D. R.—B10
Pankove, J. I.—QA3
Pao, Y. H.—GA1
Pappalardo, R.—C5
Paré, V. K.—R6
Parker, Rebecca A.—VA5
Passaglia, Elio—PA8
Patel, J. R.—U8, U9
Patrick, Lyle—NA11
Pearlstein, Edgar A.—D9
Pedersen, B.—A2
Pedrotti, L. S.—C8
Peters, P. C.—Z5
Peticolas, Warner L.—TA7, TA8
Phelps, Fred T.—D9
Philippoff, W.—MA3
Philips, J. C.—BA1, BA8
Phillipson, Paul E.—UA6
Pohl, Robert G.—V14
Pollack, S. R.—VA1
Porter, R. S.—GA2
Portis, A. M.—FA8, S7
Potter, R. F.—V7
Powers, Joseph—TA3
Powles, J. G.—JA2, P6
Pretzel, F. E.—D11
Pugh, E. W.—FA10

Queisser, H. J.—B6
Quinn, D.—F11

Rabesiaka, J.—PA5
Raney, J. K.—Y7
Rauch, C.—DA4
Ravitz, S. Frederick—FA9
Rayne, J. A.—N5
Read, P. L.—IA1
Redfield, David—NA2
Reding, F. P.—GA10
Reich, H. S.—O1
Reiss, H.—UA14
Reitz, John R.—BA4
Remeika, J. P.—E1
Reynolds, D. C.—C8, C9, C10
Rhodes, Marion—TA5
Rhodes, R. S.—P4
Rhodin, T. N.—N11
Rimai, L.—M4
Risgin, O.—E8, E9
Roberts, R. A.—X2
Robinson, W. A.—A14
Rodbell, D. S.—S3
Rogers, K. T.—DA10
Roothaan, C. C. J.—UA5
Rose, M. E.—K2
Rosenblum, B.—DA6, DA7
Rosenstock, H. B.—G1
Rosenvasser, E. S.—E6
Rosette, K. H.—FA11
Roth, Laura M.—FA5
Rothstein, Jerome—Z6
Rowland, T. J.—A10
Rubin, Robert J.—EA11
Rushing, C. C.—D11

Sack, H. S.—X9
Sack, R. A.—TA6, SP1
Sah, C. T.—B3
Salcedo, F. S.—MA10
Sancier, K. M.—C11
Sauer, J. A.—JA5, MA1, MA2
Saunders, Edward M.—F1
Schiff, L. I.—BA11
Schindler, A. I.—V6
Schlömann, E.—S8
Schlosser, H.—QA1
Schmitt, R. A.—OA7, OA8
Schone, Harlan E.—A9
Schreiner, W. N.—K6
Schultz, J.—X10
Schweinler, H. C.—Z3
Scott, Bruce L.—OA2
Scott, B. W.—N12
Segall, B.—N8, NA10
Seidensticker, R. G.—V4
Sekula, S. T.—X7
Seraphim, D.—F11, F13
Serin, Bernard—F14
Shanks, H. R.—Y3
Shapiro, Sidney—F4, F5
Shenker, H.—KA9
Shibata, A.—X9
Shiozawa, Lebo—L9
Shirley, D. A.—K7
Shockley, W.—B9
Shulman, R. G.—A5
Sidles, P. H.—Y3
Siegel, Benjamin M.—BA12
Sievers, A. J., III—S10
Sill, Richard C.—V1
Simmons, W. W.—A14
Skinner, John G.—VA6
Sladek, R. J.—Y4
Slichter, W. P.—W6
Smith, Paul H.—F5
Smith, T. B.—HA1
Smith, A. E.—W8
Smith, Charles S.—J3
Smith, G. E.—KA5
Smoluchowski, R.—D8
Snyder, L. C.—UA9
Softky, Sheldon D.—HA7
Solow, Max—U2
Sonder, Edward—D12
Soohoo, R. F.—FA14
Sosin, A.—R5
Soule, D. E.—HA2
Spicer, W. E.—C14
Spitzer, W. G.—QA4
Stamper, John—Y8
Stapleton, H. J.—M9
Statton, W. O.—PA7
Statz, H.—M4
Stearns, C. A.—U14
Stein, Joseph M.—EA12
Stein, H. J.—Z8
Stein, M. N.—MA1, MA2
Stein, Richard S.—TA3, TA4, TA5
Stephens, Charles—B7
Stickler, J. J.—DA4
Stiles, P. J.—DA5
Stockmayer, W. H.—GA8
Stratton, Robert—B12
Straub, W. Deter—HA3, Y5
Strauss, Alan J.—QA6, QA7, QA8
Strecker, Robert W.—V13
Strong, Peter F.—F4
Strutt, P. R.—U7
Suffredini, C. S.—OA7, OA8
Suhl, H.—EA2, FA8
Sutter, P. H.—IA4
Swalen, J. D.—VA2
Swartz, J. C.—X11
Swets, D. E.—X6

Tauer, K. J.—FA12
Taylor, B. N.—F6
Taylor, R. D.—K10
Taylor, T. T.—A12
Testardi, L. R.—KA4
Teutsch, W. B.—KA8
Theriault, John P.—NA6
Thompson, D. O.—R6
Thomson, R.—U3
Tinkham, M.—C13, F9, L8, S10

Title, R. S.—D3
Tolles, William M.—P9
Tomasch, Walter J.—Y11
Tomizuka, C. T.—X2
Tooper, Bernadine—V14
Tosi, Mario—VA7, VA8
Triebwasser, S.—C3
Trivisonno, J.—J3
Trumbore, F. A.—QA4
Tucker, R. N.—IA7
Tuler, Floyd R.—U11
Turner, E. H.—S5

Uehling, E.—L1

Van Lint, V. A. J.—OA7, OA8, Z9
Vant-Hull, L. L.—F3
Verdier, Peter H.—GA8
Vineyard, George H.—K4, R10
Visscher, W. M.—K10

Waddington, T. C.—SP1
Wagenblast, H.—X12
Wagoner, G.—HA6
Waldstein, P.—D11
Walecka, J. O.—Q3
Walker, L. R.—K8, K9
Wallace, Duane C.—EA4
Wallis, R. F.—EA6, EA7
Walsh, W. M., Jr.—E5
Wannier, G. H.—BA2
Ward, Raymond L.—P2
Watkins, G. D.—Z1
Watson, R. E.—A7, UA10
Webb, W. W.—V3
Weber, M. J.—M4
Wechsler, M. S.—R9
Weeks, R. A.—Z11
Weger, M.—FA8
Weil, John A.—P8
Weiser, Kurt—QA9
Weiss, A. W.—UA2
Weiss, R. J.—FA12
Weiss, W. L.—B15
Weissman, S. I.—T2
Wernick, J. H.—A6, A8
Wert, Charles—X8
Wertheim, G. K.—K1, K8, K9
Wheeler, R. G.—NA7, NA8
White, Ray H.—L8
White, R. L.—CA3
Widmer, H.—U10
Wieder, H. H.—L7
Wiegand, C. E.—Q2
Wiegand, D. A.—D8
Wigen, P. E.—E10
Wikner, E. G.—Z9
Wilchinsky, Zigmond W.—MA6
Wilets, L.—Q1
Wilkinson, M. K.—CA2
Williams, E. Allan—I4
Williams, G. A.—A4
Williams, Wendell S.—IA2
Wilsdorf, H. G. F.—U7
Wilson, Philip—TA5
Wilson, Richard E.—OA6
Winter, Robert M.—J6
Wiser, Nathan—EA1
Woll, E. J.—N1
Wise, H.—C11
Wolf, J. D.—X13
Wolfe, R.—KA5, QA5
Wood, Van E.—BA4
Woodbury, H. H.—E12, E13
Woodmansee, W. E.—P11
Woodruff, Truman O.—L2
Woodward, A. E.—JA5, MA1
Wright, George B.—QA6
Wu, T. S.—JA6
Wullaert, R. A.—R7
Wyckoff, Harold W.—W4
Wyluda, B. J.—A5

Yang, J. W.—JA7
Yoshimine, M.—UA5
Young, C. G.—E3, E4
Young, F. W., Jr.—U1

Zeiger, H. J.—DA4
Zwanzig, Robert—EA11
Zwerdling, Solomon—NA6

Preliminary Announcement of the 1961 Spring Meeting

The 1961 Spring meeting will be held in Washington, D. C., on Monday, Tuesday, Wednesday, and Thursday, April 24–27. The headquarters hotel is the Sheraton-Park. The sooner you write to it for your room, the better. This advice is given early and emphatically, because last year there were more of our members who asked for rooms than there were rooms set aside for them (an event unprecedented in our history, by the way) and the Local Committee was hard put to it to get a supplementary quota. If this situation is destined to arise again this year, the sooner it arises the better will be the chance of remedying it. Therefore write as soon as possible for your room and do not fail to mention that you are coming to the meeting of The American Physical Society. Deadline will be February 10.

Preliminary Announcement of the 1961 Mexico Meeting*

(Three copies of each abstract, please!)

Those who attended either of our two previous meetings in Mexico will be delighted, and all others should be allured, by the news that arrangements for the meeting of June 22–24, 1961, are well under way. This, like the Congress of 1955, will be a joint meeting of the Sociedad Mexicana de Fisica and our Society, and its scene will be the Ciudad Universitaria on the southern boundary of Mexico City. Committees each composed of a member of each Society are now planning groups of invited papers in cosmic-ray physics, low-energy nuclear physics, theoretical physics, and solid-state physics. Our Divisions of Electron Physics, Fluid Dynamics and Plasma Physics will all three take part.

Deadline will be Friday, April 7. Abstracts are to be sent to the office of the Society at Columbia University, New York 27, New York. *Three copies of each abstract are requested:* one copy will be sent forthwith to Mexico City for translation into Spanish and publication in the announcement of the Sociedad Mexicana de Fisica.

Rooms have been booked for our members in hotels of three categories. The *de luxe* category includes the Hotel del Prado, Alffer, Bamer, Continental Hilton: its price range is $16 to $13.60 double, $14 to $12 single. Of the "superior first-class" category are the Cristobal Colon, San Francisco, Diplomatico ($10 to $8 double, $7.20 to $8 single). Of the "first-class" category are the Prince, Regis, Metropol ($8.80 to $6.80 double, $7.60 to $4.80 single). These prices are quoted in U.S.A. currency; they do not include any meals.

All hotel reservations are to be made by writing to Pancho Lona Tours Balderas 32 (primer piso), Mexico 1, D.F., Mexico. Use 7-cent airmail stamp. Make deposit for one night when you make your reservation; it will be refunded if you give 72 hours notice of cancellation. All reservations are to be made before June 10.

* Item added in proof and not proofread.

1961 International Conference on Photoconductivity

The "1961 International Conference on Photoconductivity" will be held at Cornell University, Ithaca, New York, on August 21–24. This is accepted as a "topical conference" by The American Physical Society, and other sponsors are the International Union of Pure and Applied Physics and the Office of Naval Research. The emphasis of this conference will be on the fundamental aspects of photoconductivity and phenomena directly related thereto. The conference will conform to the pattern of the 1954 conference on photoconductivity held at Atlantic City. Parallel sessions will not be allowed, and so the programme must include not more than about twenty half-hour papers and forty 15-minute papers, probably only a small percentage of those that may be contributed. Papers on specific devices and applications will be excluded. All members of the Society are allowed to attend this Conference, but those who wish to go must signify their wish **not later than July 1** to the Conference Secretary, Dr. A. R. Hutson, Bell Telephone Laboratories, Murray Hill, New Jersey. To him must go also the abstracts of contributed papers, and these must conform to the same rules as are imposed on those submitted to general meetings of the Society. **Deadline for abstracts is March 31, 1961.**

1961 Gaseous Electronics Conference

The 1961 Gaseous Electronics Conference, fourteenth of the series, will be held at the General Electric Research Laboratories ("the Knolls") at Schenectady, New York, on October 11–13. Former conferences were sponsored by our Division of Electron Physics, which still contributes a member to the Organizing Committee. This Conference has been accepted as a Topical Conference of The American Physical Society. Like its predecessors it is to deal with the basic collision processes occurring in ionized gases, with the mechanisms of electrical breakdown and those of operation of electrical discharges, and with plasma physics in general, but papers on specific devices are excluded. All members of the Society have the right to attend this Conference and to submit contributed papers, but the Organizing Committee may accept or reject these as it chooses.

Abstracts of contributed papers are to be sent to C. J. Gallagher, General Electric Research Laboratories, Schenectady, New York, and must reach him not later than August 25, 1961. Abstracts must conform to the same regulations as are imposed on those submitted for general meetings of the Society. The Organizing Committee will not accept a greater number of contributed papers than is compatible with its intent to keep the meeting within three days, to avoid simultaneous sessions, and to provide adequate time for presentation and discussion of the papers that are accepted.

1961 Spring Meeting of the New York State Section

The 1961 Spring Meeting of the New York State Section will be held on Friday and Saturday, April 14 and 15, at Lemoyne College, Syracuse, New York. It will consist principally of a symposium on atomic and molecular amplifiers, comprising masers of various kinds. Advance registration by mail will be required, since the space available is limited. This should be made by writing to Oran E. Miller, B-65, 1669 Lake Avenue, Kodak Park, Rochester 4, New York. Additional information about the meeting may be obtained from him.

Important Notice to Members and Fellows of The American Physical Society

A new Membership List of The American Physical Society will be issued in 1961, and it is highly desirable that this be as nearly complete as possible. By the time you read this you should have received by first-class mail, in a window envelope, a return-addressed postal card bearing your name and address of present record, together with instructions for its immediate return emended as necessary. If you have not received this postal card, notify the undersigned of your name and address as you wish them to appear in the Membership List. If your professional affiliation does not appear in your address, this additional information is requested.

SHIRLEY L. QUIMBY
Pupin Physics Laboratories
Columbia University
New York 27, New York

Proceedings of the American Physical Society

Minutes of the Second Annual Meeting of the Division of Plasma Physics Held in Gatlinburg, Tennessee, November 2–5, 1960

THE Second Annual Meeting of the Division of Plasma Physics of the American Physical Society was held in Gatlinburg, Tennessee, from November 2–5, 1960. Clear, cool weather and the peak of the leaf coloring in the Smoky Mountains combined to provide a lovely backdrop to the scientific meetings. There were 120 contributed papers divided almost equally between theory and experiment. The total registered attendance was 358 which, as usual, exceeded all preliminary estimates. A most welcome addition at the conference were a number of contributed papers, together with scientific delegations, from France and the United Kingdom.

The local conference committee consisted of A. Simon, G. C. Kelley, R. J. Mackin, Jr., and H. Postma, all of Oak Ridge National Laboratory. Union Carbide Nuclear Company was host at a reception on Wednesday evening and at a social hour preceding the banquet Thursday evening. The banquet featured a welcoming address by the distinguished "rock-burning" director of the Oak Ridge National Laboratory, A. M. Weinberg, followed by the principal speaker, J. L. Tuck, who did not extol "sea-burning" but instead presented an interesting series of slides taken on his recent trip to the USSR. The continued high attendance, both at the conference and at the individual sessions therein, again illustrates the intense upsurge of interest in plasma physics which has occurred in recent years.

ALBERT SIMON
Local Chairman

Stability Theory

A1. Collective Variables for a Plasma.* CHARLES R. WILLIS, *Boston University.*—A set of collective variables introduced by Gross[1] are used to obtain dispersion relations for a plasma. The new variables are generalizations of the components of the Fourier transform of the density introduced by Bohm and Pines.[2] The equations satisfied by these variables are demonstrated, and approximations are introduced in a manner such that the effect of collisions can be studied systematically. One of the results of the approximations is the appearance in the equations of the correct equilibrium pair distribution function which has two immediate consequences: the Debye length is not introduced explicitly, but is contained in the pair distribution function, and the dispersion relations contain the velocity of sound obtained from the equation of state of a plasma instead of the velocity of sound of an ideal gas. In the limit as the wave number goes to zero, rigorous solutions for the collective variables are obtained.

* Supported by the U. S. Air Force Cambridge Research Center.
[1] E. P. Gross, "Dynamics of classical many-body systems," AFCRC Rept.
[2] D. Bohm and D. Pines, Phys. Rev. 85, 338 (1952).

A2. Instabilities Due to Anisotropic Velocity Distribution.* W. E. DRUMMOND, M. N. ROSENBLUTH, AND M. L. JOHNSON, *General Atomic.*†—It has been shown by Harris[1] that, in a uniform plasma for which the ratio $T_\perp/T_\parallel$ (temperatures perpendicular or parallel to the uniform magnetic field) is infinite, longitudinal plasma oscillations with frequencies equal approximately to integral multiples of the ion cyclotron frequency are unstable. If the ratio $T_\perp/T_\parallel$ is one, no such instabilities occur. In actual practice, such as in a mirror machine, the ratio $T_\perp/T_\parallel$ may be as high as 3 or 4 for the ions whereas the electrons should have a ratio $T_\perp/T_\parallel$ of approximately one. Thus it is important to determine the minimum value $T_\perp/T_\parallel$ for the ions for which these instabilities occur. We have investigated this by machine calculation of the longitudinal part of the conductivity tensor. The result is that $T_\perp/T_\parallel$ for the ions must be greater than 8 or 9 for the instabilities to occur. In addition, Harris predicts similar instabilities at integral multiples of the electron cyclotron frequency. We have established the fact that the value of $T_\perp/T_\parallel$ for the electrons must always be greater than 2 for these instabilities to occur.

* Research on controlled thermonuclear reactions is a joint program carried out by General Atomic and the Texas Atomic Energy Research Foundation.
† John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic Division of General Dynamics Corporation, San Diego, California
[1] E. Harris, Proceedings of the Conference on Theoretical Aspects of Controlled Fusion Research, Gatlinburg, Tennessee, April 27, 28, 1959, ORNL-2805.

A3. On Plasma Turbulence.* CARL OBERMAN, *Project Matterhorn, Princeton University.*—In a recent article by G. Rosen,[1] the Hopf[2] functional differential equation, describing the time evolution of the characteristic functional (or Fourier transform) of an arbitrary phase distribution of hydrodynamical systems each satisfying the incompressible Navier-Stokes equation, has been given a general solution in the form of an integral representation. Integral representation of the spatial correlation functions are derived from this closed form expression of the characteristic functional by functional differentiation. In the present paper a corresponding treatment is given for the full Vlasov set of equations. One regards the collisionless Boltzmann equation (together with Maxwell's equations) as describing the exact motion of a fluid in the phase space. The same progress can be made with this set of equations because the nonlinearity is essentially the same type as in the N-S equation, that is, quadratic. In a second paper[3] Rosen has an explicit description of the initial decay of turbu-

lence from an idealized initial state. The corresponding treatment for the Vlasov set can be given here.

* Work accomplished under the auspices of U. S. Atomic Energy Commission.
[1] G. Rosen, Phys. Fluids 3, 519 (1960).
[2] E. Hopf, J. Rat. Mech. Anal. 1, 87 (1952).
[3] G. Rosen, Phys. Fluids 3, 525 (1960).

A4. Excitation of Plasma Waves in Opposing Electron and Ion Streams.* HEINRICH DERFLER, *Stanford Electronics Laboratories, Stanford University.*—Plasma waves may be excited by feeding currents into the streams through a pair of grids. The resulting convection current has been calculated as a function of the total driving current by applying Laplace transformation in time and Fourier transformation in space to Maxwell's and Boltzmann's equations for electrons and ions. The subsequent analysis was restricted to an initial δ-distribution in velocity. By following the correct Laplace integral path, one decides automatically in which direction the excited waves propagate relative to the grids and whether the instabilities are convective[1] or not. Only evanescent waves and nonconvective instabilities occur with opposite particle motion. For two mutually neutralizing streams of equal drift energy, the conductance of the gap between the grids is regenerative in the frequency range $0<\omega<2^{\frac{1}{2}}\omega_{pi}$ and in some isolated higher frequency bands, if the gap width exceeds $\sqrt{2}\pi u_i/\omega_{pi}$. This negative conductance may be associated with cathode sheath oscillations and noise in low pressure discharges.

* Work supported by Wright Air Development Division, U. S. Air Force.
[1] P. A. Sturrock, Phys. Rev. 112, 1488 (1958).

A5. Electrostatic Instabilities in Nonuniform Plasmas.* E. FRIEMAN AND A. PYTTE,† *Project Matterhorn, Princeton University.*—As is now well known, a number of electrostatic instabilities have been found in plasmas which are spatially uniform but whose velocity distribution functions are not monotonically decreasing. It is also of interest to ask whether spatial inhomogeneities can lead to electrostatic instabilities. One such instability which is caused by density gradients will be discussed. Two methods will be presented for investigating this problem. The first is a perturbation procedure for the case in which the inhomogeneity is slight. The second is a WKB procedure applicable when the equilibrium quantities are slowly varying functions of position. A sufficient condition for stability against short wavelength oscillations is obtained in this latter case.

* Work accomplished under the auspices of U. S. Atomic Energy Commission.
† Now at Dartmouth College, Hanover, New Hampshire.

A6. Approximate Solution of Wave-Propagation Problems by Means of a Variation Principle. E. BARSTON AND P. A. STURROCK, *Microwave Laboratory, W. W. Hansen Laboratories of Physics, Stanford University.*—A variation principle is described by which small-amplitude disturbances of a plasma may be investigated when collisions may be neglected. This variation principle lends itself to the approximate solution of complicated problems by the method of trial functions. If, for instance, the plasma is uniform in the z direction but nonuniform in the x and y directions, one may obtain an approximation to the dispersion relation which characterizes wave propagation in the z direction. The dispersion relation so obtained is of a better order of accuracy than the trial functions by which it was derived. Such calculations have been made for simple models for which analytical solutions are available for comparison. The technique may be used to study normal propagation, wave amplification, or instability.

A7. Electrical Conductivity of a Collision-Free Plasma.* H. E. PETSCHEK, *Avco-Everett Research Laboratory.*—The resistivity produced by a random distribution of waves in a plasma in which interparticle collisions can be neglected is considered. Up to first order in wave amplitude, the waves do not produce the required "friction" force between electrons and ions. However, the nonlinear interactions, or collisions,[1] between waves do produce such a force, if the distribution of energy in wave number space is asymmetric. In the presence of a current the distribution becomes asymmetric, resulting in a force proportional to the current. The waves which are most effective in producing a high resistivity are magnetohydrodynamic waves with frequencies in the neighborhood of the ion cyclotron frequency. For these waves the resulting conductivity is $\sigma_{\text{anom}}=8Ne^2/(m_e\omega_{ci}\beta_v^2)$, where β_v is the ratio of wave pressure to magnetic pressure. This agrees within a factor of three with stabilized pinch experiments[2] if all of the measured plasma pressure is assumed to be due to waves.

* Sponsored by the Office of Naval Research.
[1] F. J. Fishman, A. R. Kantrowitz, and H. E. Petschek, Revs. Modern Phys. 32, 959 (1960).
[2] S. A. Colgate *et al.*, *Second International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958* (1959), Vol. 32, p. 129.

A8. Electromagnetic Interaction of a Beam of Charged Particles with Plasma. JACOB NEUFELD AND P. H. DOYLE,* *Oak Ridge National Laboratory.*†—The plasma-beam instability has been studied by Akhiezer and Fainberg under the assumption that $\theta=0$, where θ is the angle formed by the beam and the direction of the growing wave. Under these conditions the interaction is electrostatic. In this investigation the assumption is generalized so as to include $\theta\neq 0$ and the effect of electromagnetic interaction. For $\omega\sim\omega_1$, where ω_1 is the Langmuir frequency of the plasma, the interaction is electrostatic for all values of θ, and the resulting instability which produces a longitudinal wave increases exponentially in accordance with the term $\exp(3\sqrt{3}\omega_0^2 k v_0\cos\theta/8)^{\frac{1}{3}}t$ (where ω_0 is the Langmuir frequency of the beam). For a frequency range below ω_1 the instability is less pronounced. However, this instability is significant since the interaction is electromagnetic and the resulting "growing wave" is characterized by an electric vector having both transverse and longitudinal components. An assumption was made that the density of the incident beam is small, and the results cover all values of θ except those close to $\pi/2$. For $\theta\sim\pi/2$ the assumption is more general, and thus the results apply to any density of the beam.

* Now at Michigan State University, East Lansing, Michigan.
† Operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

A9. Nonlinear Stationary Plasma Oscillations.* HANS K. WILHELMSSON, *Project Matterhorn, Princeton University.*—We investigate the frequency of nonlinear free oscillations in the following one-dimensional situations: (1) the cold plasma including ion motion, (2) the plasma with a spread in the velocity distribution, and (3) the two-stream case. In each case we obtain a dependence of the frequency on the degree of nonlinearity. Our method of solution is to expand in the mass ratio and in the ratio between the velocity-spread (or velocity-separation) and the phase velocity. With regard to nonlinearity we can then treat the oscillations exactly. In the two-stream case our nonlinear solution tends toward the nongrowing solution of the linearized case for small amplitudes.

* Work accomplished under the auspices of the U. S. Atomic Energy Commission.

A10. Stability of Cold Nonlinear Traveling Waves.* E. ATLEE JACKSON, *Project Matterhorn, Princeton University.*—Akhiezer and Lyubarskii[1] were the first to obtain the solution for nonlinear traveling waves in a one-dimensional plasma where the ions are infinitely massive and the electrons are cold (i.e., $fe(x,v,t)=n(x,t)\delta[v-u(x,t)]$. This solution is a subclass of the solutions discussed by Dawson,[2] who applied a Lagrangian analysis to the system of charged sheets. Although it is clear from the work of Dawson that these waves are stable,

it is of some interest to see how this is established from the usual Eulerian equations. Such a proof is given, provided the perturbation is bounded in space, and the infinity of eigenfunctions going as $e^{i\omega t}$ are explicitly demonstrated. These eigenfunctions are almost periodic functions of space, rather than simply periodic.

* Work accomplished under the auspices of U. S. Atomic Energy Commission.

[1] A. I. Akhiezer and G. Ya Lyubarskii, Doklady Akad. Nauk, S.S.S.R. **80**, 193 (1951); S. F. Smerd, Nature **175**, 297 (1955).

[2] J. M. Dawson, Phys. Rev. **113**, 383 (1959).

A11. An Investigation of Transport Properties of Plasmas.* KAYA IMRE, *University of Michigan*.—The lack of a general technique for a proper treatment of the transport properties of plasmas has been long recognized. However, it has been shown that some of the electromagnetic properties may be studied with considerable success using the linearized Boltzmann-Vlasov equation. The purpose of this presentation is to attempt to investigate the possibility of a generalization of this formalization so that an "appropriate"—in the sense that the results of the former analyses may be re-deduced when certain approximation procedures are employed—study of the transport properties may be performed. It is assumed that the necessity of a dissipative mechanism for such an investigation may be represented adequately by a relaxation type collision model. The first-order perturbations of these properties are computed in such a form that the transport parameters can be identified by inspection. The elementary relationships among these parameters are shown to be satisfied, although their mathematical structures, being similar to those encountered in the microconductivity studies, differ considerably from that of the results obtained by the ordinary methods. Special attention has been given to the diffusion processes across magnetic fields, and a possible explanation of the experimentally observed high diffusion rates has been proposed.

* The research reported here was supported in part by the Air Force Research Division, Air Research and Development Command, U. S. Air Force.

A12. Equilibria Satisfying Newcomb's Stability Criterion. K. J. WHITEMAN AND D. M. COPLEY, *Atomic Energy Research Establishment, Harwell*.—A numerical test of the stability of hydromagnetic equilibria has been obtained using Newcomb's necessary and sufficient condition. This has been applied to some one-parameter families of equilibria that for low values of the parameter are unstable and for high values are obviously stable.

A13. Calculations on the Collapse of a Fully Ionized Plasma. K. HAIN, *Max-Planck-Institut für Physik und Astrophysik, Munich*, AND K. V. ROBERTS, *Atomic Energy Research Establishment, Harwell*.—The magnetohydrodynamic equations for a fully ionized cylindrical plasma have been programmed in the IBM Fortran. An analysis of the behavior of a fast Z-pinch is presented.

A14. Cartesian Tensors and Spherical Harmonic Expansions in Boltzmann's Equation. T. WYATT JOHNSTON, *RCA Victor Research Laboratories*.—Difficulties encountered in extending the spherical harmonic expansions to higher terms can be evaded neatly by converting to the appropriate Cartesian tensor expansion. The dependence of such things as non-isotropic pressure terms on spherical harmonics is then clearly shown. The substitution into the Boltzmann equation and the decomposition into component equations are straightforward. One is still left free to choose the speed-dependent expansion in any way that seems convenient.

Plasma and Ion Production and Acceleration

B1. Electrodeless Plasma Gun. C. LELOUP, J. P. POFFE, D. VERON, AND F. WAELBROECK, *Association Euratom-CEA, Fontenay-aux-Roses*.—A fast-acting valve injects small amounts ($\lesssim 0.6$ cc NTP) of deuterium into an evacuated tube. A 10-μf condenser bank is then discharged into a single conical loop surrounding this tube. The accelerated plasma penetrates into a guiding magnetic field (2400 gauss), parallel to the tube axis. The radial distribution and total momentum of the plasma beam were determined by small and large ballistic pendula; its velocity, approximate longitudinal shape, and time of ejection from the gun were observed by photomultipliers and magnetic loops surrounding the tube. These parameters were measured as functions of the amount of gas injected, the time elapsed between the opening of the valve and the firing of the gun, the condenser bank energy (up to 3 kj) and the mutual initial orientation (parallel or antiparallel) of the gun and guiding magnetic fields. Without pre-ionization and 50 cm from the gun, the plasma has approximately a diameter of 4 cm and a length of 50 cm. The average density and velocity are, respectively, 4.10^{15} ions cm^{-3} and 14 cm/μsec^{-1} (3 kj and 0.6 cc D_2). A weak pre-ionization has already a pronounced effect; experiments with a stronger H.F. pre-ionization are in progress.

B2. Experiments and Theory on Continuous (Steady) Plasma Acceleration. R. V. HESS, J. MALENDA, AND J. BURLOCK, *NASA Langley Research Center* (introduced by J. S. EVANS, Jr.).—A method of continuous plasma acceleration has been devised which aims to provide efficient ionization of the plasma and uniform distribution of heating of electrodes to avoid formation of localized discharges. The experimental arrangement utilizes coaxial electrodes together with an externally imposed magnetic field gradient. The radial current together with the axial magnetic field component yields a circular motion of electrons which aids in the ionization as in the Phillips ionization gauge. The circular "Hall" current together with the radial component of the magnetic field provides axial acceleration; experimental and theoretical evidence for the Hall current mechanism is provided. The "Hall" current operation is contrasted with that in the Homopolar device where a large part of the plasma is set into rotation. Other electrode and magnetic field configurations designed to avoid localized discharges also have been investigated with emphasis on hollow cathodes.

B3. Analysis of Steady-Flow Plasma Accelerator. GEORGE P. WOOD, *NASA Langley Research Center* (introduced by J. S. Evans, Jr.).—An analysis of the steady-flow dc plasma accelerator has been developed from the equations of motion of the three components of the plasma for the conditions of small degree of ionization, constant static temperature, and Lorentz force oriented along the channel axis. Previous analyses[1,2] yielded the necessary variation with axial distance of one component only (that perpendicular to the channel axis) of the applied electric field. The new analysis supplies the correct variation of both electric-field components and also provides solutions for the velocity vectors of each of the three plasma components. This information is needed for proper design of an accelerator. The correct expression for the joule heating in the accelerator is shown to be the customary j^2/σ, where σ is evaluated for B equal to zero, plus an additional

term proportional to the square of the slip velocity between ions and neutral particles.

[1] R. J. Rosa, Ph.D. Thesis, Cornell University, 1956.
[2] G. P. Wood and A. F. Carter, *Dynamics of Conducting Gases* (Northwestern University Press, Evanston, 1960).

B4. Magnetic Ignition of a High-Voltage Mega-Amperage Low-Pressure Discahrge. K. THOM AND J. NORWOOD, JR., *NASA Langley Research Center* (introduced by J. S. Evans, Jr.).—A magnetic field transverse to the electric field alters the breakdown voltage for a system of coaxial electrodes carrying an electrical potential. For given values of the pressure multiplied by the distance between the electrodes, the breakdown voltage depends on the magnetic flux density. At low pressure, Townsend's first ionization coefficient depends on the electron Larmor radius and the electron drift velocity $[E\times B]/(B\cdot B)$ rather than on the mean free path and E. For large B the electron transit time exceeds the ion transit time, and thus the formative time lag becomes a function of B. For a pressure of 10^{-2} mm Hg, the theory shows the feasibility of using a magnetic field for triggering a high-voltage discharge in a coaxial type of plasma gun, where a breakdown, according to the Paschen curves, cannot occur. Experimentally, a million-ampere discharge of a capacitor bank was achieved through magnetic ignition, with a rise time of the current of less than 2 μsec.

B5. Plasma Electric Field Distribution in a Coaxial Accelerator.* L. C. BURKHARDT AND R. H. LOVBERG, *Los Alamos Scientific Laboratory.*—If the voltage between the electrodes of a coaxial plasma gun is measured ahead of the advancing current sheath, a voltage should be observed which is due to plasma resistance and electrode sheath drops. In a plasma carrying 10^5 amp of radial current, this voltage was slightly less than 100 v, which would imply a plasma temperature of less than 5 ev if resistance were responsible. Measurements with a double voltage probe showed, however, that nearly the entire drop is due to a cathode sheath over the center conductor. The substitution of He for D_2 approximately doubles the sheath voltage. When the current layer crosses the electric probe position, an additional field component due to $\mathbf{v}\times\mathbf{B}$ appears. The velocity computed from E and B measured at a single point agrees within experimental errors with the velocity obtained from a two-point magnetic probe measurement.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

B6. High Current, 600-kv Accelerator for DCX-Type Injection. G. G. KELLEY, N. H. LAZAR, R. C. DAVIS, AND R. R. HALL, *Oak Ridge National Laboratory.**—An accelerator tube designed to handle currents of several hundred milliamperes up to voltages of 600 kv has been constructed and put into operation. The over-all tube length is 24 in. with a beam path inside of 18 in. The design includes shielding of all insulator surfaces in line of sight from the beam. No radial focusing of the beam is used until the particles have reached full energy. Thus, beam diameters may be maintained sufficiently great to reduce the effects of space charge spreading for the path lengths required following acceleration. The focusing and handling of the beam following acceleration will be discussed in reference to injection into a device such as DCX.

* Operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

B7. Mass Analysis at Large Ion Currents from the Duo-Plasmatron Ion Source. O. B. MORGAN, G. G. KELLEY, N. H. LAZAR, AND E. C. MOORE, *Oak Ridge National Laboratory.**—The von Ardenne type "duo-plasmatron" ion source has been operated to yield currents in excess of 340 ma at 80 kev. For various source geometries, the Pierce limit

$$I=\frac{1.71\times10^{-7}V^{\frac{3}{2}}}{(Z/r_0)^2A^{\frac{1}{2}}}$$

has been verified. The current output as a function of various source parameters has been studied. An einzel lens capable of focusing currents up to 100 ma and an analyzing magnetic field have been used to determine hydrogen ion mass ratios for currents in this range. Under optimum source conditions 70–80% of the current in the range 20–50 ma was H_3^+. In the range 50–100 ma, 60–70% H_2^+ ion fractions have been measured. Variation in the relative fractions have been observed depending, particularly, on gas feed and the intermediate electrode canal geometry and its spacing to the anode. Under certain operating conditions, in excess of 50% H^+ could be obtained.

* Operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

B8. Electrostatic Ion Extraction from a Plasma Surface.* JOHN R. BANISTER AND JOHAN G. BELINFANTE,† *Sandia Laboratory.*—We have examined experimentally and theoretically the extraction of ions from a plasma surface. Experimentally, this was accomplished by generating a plasma flow with a magnetic shock tube and allowing it to impinge upon a diaphragm which was destroyed upon contact. The plasma then flowed into a vacuum across which a constant voltage was applied. A set of equal potential rings was placed about the high voltage region to insure a space charge limited voltage distribution. The theory behind the experiment has been derived, assuming the plasma flow into the vacuum obeys the usual rarefaction equations. Conservation of mass, momentum, and energy along with Maxwell's equations show that the the ion current flow and distribution is described by Child's law. On combining this result with the material flow equations it was found that the surface from which the ions are emitted corresponds to a characteristic of the expansion fan for an infinite tube. The theory was then readily modified for a finite tube. The experimental observations of the ion current time history are commensurate with theory.

* Work performed under the auspices of U. S. Atomic Energy Commission.
† Now at Palmer Physical Laboratory, Princeton University.

B9. Production of a Quasi-Thermalized Plasma Using a Penning Discharge. R. G. MEYERAND, JR., AND F. SALZ, *United Aircraft Research Laboratories.*—A Penning discharge (PIG)[1] has been used to produce a high-energy plasma beam. The operating characteristics of the PIG discharge are discussed in terms of the measured parameters of the plasma beam, such as density (range $10^{10}-10^{13}$ p/cc) and ion and electron energy (range 0–300 ev). The potential gradients which eject ions from the discharge have been measured and will be considered theoretically. Schemes to thermalize the beam and produce a high-temperature plasma will be discussed. A theoretical model of the discharge and the plasma will be presented and compared with the experimental results.

[1] R. G. Meyerand, Jr., and F. Salz, Bull. Am. Phys. Soc. Ser. II, 5, 366 (1960).

B10. Role of Helium Metastables in a Pulsed Hollow Cathode Discharge. C. R. BURNETT, *The Pennsylvania State University.*—A condensed discharge in a Schuler type hollow cathode filled with He at 2-mm Hg pressure produces a current pulse which peaks at 2 μsec and decays exponentially with a 4-μsec time constant. The He I spectrum exhibits a pulse at 2 μsec and a second pulse at 15 μsec which finally decays exponentially with a decay time of 75 μsec. The existence of the second light pulse is attributed to ionization and excitation

by helium metastables. This ionization mechanism has been observed by Biondi in another experiment.[1] Line profiles of $\lambda 5015\ 2^1S-3^1P$ and $\lambda 3889\ 2^3S-3^3P$ obtained with a pressure controlled Fabry-Perot interferometer show broadening and shift during the first pulse and return towards the initial shape during the second pulse. The shifts are consistent with a quadratic Stark effect produced by a peak ion density of $10^{14}-10^{15}/cm^3$. The $\lambda 3889$ line profile also indicates absorption by the metastables in the discharge region. This interpretation is borne out by the observation that the transitions to metastable states show a second/first peak light ratio which is several times smaller than the ratio for transitions which do not terminate at a metastable state.

[1] M. A. Biondi, Phys. Rev. **82**, 453 (1951).

B11. A Hot-Cathode Reflex Discharge.* FRANCIS F. CHEN AND ROBERT BINGHAM, *Project Matterhorn, Princeton University.*—A "reflex" discharge, 300 cm long and 5 cm in diameter, in 4000 gauss (±1%) has been studied. To avoid irregularities in emission and to increase the percentage ionization, a thick tungsten disk, 5.7 cm in diameter, heated to 2700°K by electron bombardment, was used as a cathode. At 3-μ He, densities of 5×10^{12} were achieved at 15 amp; larger currents do not appreciably increase the density. At this pressure classical diffusion cannot account for the electron current across the magnetic field to the anode. Large fluctuations in potential were observed on Langmuir—predominantly low-frequency (below 200 kc) and about 4 v peak-to-peak on the axis of the discharge, increasing several-fold toward the edge. The probes revealed an approximately parabolic dc floating potential rising from nearly the cathode potential on the axis to the anode potential of about 70 v just outside the discharge. The rotation frequency computed from this radial electric field agrees roughly with a peak in the frequency spectrum of the oscillations and with streak photographs. Probe characteristics are exponential over several decades in electron current, indicating temperatures around 3 ev on the axis and above 5 ev near the edge.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

B12. Electron Cylotron Resonance Heating. W. B. ARD,* R. A. DANDL, H. O. EASON, AND R. J. KERR, *Oak Ridge National Laboratory.*†—A dc coaxial plasma gun was used to inject plasma into a microwave cavity located in the midplane of a small magnetic mirror machine. Preliminary results indicate electron temperatures of the order of 100 v at electron cyclotron resonance. Planned experiments which include simultaneous ion and electron heating will be discussed.

* Consultant from University of Florida, Gainesville, Florida.
† Operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

Kinetic Theory and Radiation

Invited Papers

C1. A One-Dimensional Plasma Model. JOHN M. DAWSON, *Project Matterhorn, Princeton University* (30 min.)

C2. Spontaneous Fluctuations in a Plasma. NORMAN ROSTOKER, *General Atomic.* (30 min.)

C3. Stability of the rf Pinch on the Free Particle Model. ERICH S. WEIBEL, *Space Technology Laboratories.* (30 min.)

Contributed Papers

C4. Effect of Electrostatic Instability on the Basic Assumptions of Bogoliubov's Kinetic Theory for a Plasma.* ANDREW LENARD, *Project Matterhorn, Princeton University.*—The basis of Bogoliubov's general kinetic theory[1] is the assumption that the time scale on which the single particle distribution function f_1 varies is long compared with the time scale on which the higher distribution functions $f_n(n\geq 2)$ vary. Usually this condition is fulfilled in a spatially homogeneous plasma, because f_1 changes significantly over times $T_r=m^{\frac{1}{2}}(kT)^{\frac{1}{2}}n^{-1}e^{-4}[\ln(kT)/e^2n^{\frac{1}{3}}]^{-1}$ ("collisional relaxation time"), whereas the $f_n(n\geq 2)$ change in times of the order $T_p=m^{\frac{1}{2}}/n^{\frac{1}{2}}e$ ("period of an electrostatic oscillation"). The ratio of the two quantities is $T_r/T_p=\Lambda^{\frac{1}{2}}/\ln\Lambda$, $\Lambda=kT/e^2n^{\frac{1}{3}}$ which is large when the mean kinetic energy is large compared to the mean Coulomb energy. However, when f_1 is electrostatically unstable, this condition is no longer fulfilled, since f_1 also varies on the time scale T_p. Thus one would expect that the functional dependence of $f_n(n\geq 2)$ on f_1 postulated by Bogoliubov ceases to be valid in this case. It can be shown explicicitly how this lack of determination arises when f_1 is unstable. When f_1 is stable, $f_n(n\geq 2)$ is completely determined in the sense of Bogoliubov as a functional of f_1.

* Work accomplished under the auspices of the U. S. Atomic Energy Commission.
[1] N. N. Bogoliubov, "Problems of dynamical theory in statistical physics," Section 11, Moscow, 1946 (in Russian). (See also English translation by E. K. Gora, U. S. Air Force Cambridge Research Center, Publication TR-59-235.)

C5. Quantum Kinetic Equations for Plasma and Radiation. P. B. BURT AND E. G. HARRIS, *The University of Tennessee.*—By defining a density matrix for a system of interacting particles and electromagnetic fields, it is possible to replace the Schrödinger equation for the state vector of the system by a "Liouville" equation for the density-transition matrix describing the system.[1] It is then shown that integration over some of the particle and oscillator variables leads to a hierarchy of coupled equations for the "reduced" density matrices of various orders, in close analogy to the classical situation.[1,2] Finally, a perturbation expansion in powers of the charge of the particles, with suitable assumptions about the volume of the system, number of particles and particle mass, is shown to lead to the quantum mechanical analog of the Vlasov equations for plasma and radiation.

[1] P. Lowdin, Phys. Rev. **97**, 1474 (1955).
[2] A. Simon and E. G. Harris, Phys. Fluids **3**, 245 (1960).

C6. Photon Transport Theory.* E. H. KLEVANS AND R. K. OSBORN, *The University of Michigan.*—A first-order, momentum-configuration space transport equation for photons is derived for low-energy (nonrelativistic) systems. The derivation is first order in the sense that the transition probabilities characterizing photon scattering emission and absorption are computed only to the first nonvanishing order by conventional perturbation methods. The present approach provides an essentially axiom-deduction development of the theory of

radiative transfer (albeit via several ill-evaluated approximations) within the context of which various processes and their inter-relationships may be investigated. Most of these processes have hitherto been studied only phenomenologically and usually piecemeal. Specific application to photon scattering, cyclotron radiation, recombination radiation, de-excitation radiation, and bremsstrahlung is made in the text. The derivation of an H theorem for photon-particle systems is sketched, and contact is made with the usual statistical mechanical treatment of the equilibrium states of such systems. It also is shown that some aspects of collective particle behavior can be introduced quite naturally into the description of photon transport in the fully ionized plasma.

* The research reported here was supported in part by the Advanced Research Projects Agency and the U. S. Army Signal Research and Development Agency.

C7. Cyclotron Radiation from Relativistic Particles with an Arbitrary Velocity Distribution. LUDWIG OSTER, *Laboratory of Marine Physics, Yale University.*—The spectral and angular behavior of cyclotron radiation is derived for a particle that has arbitrary velocity components along and across the magnetic field in a certain reference frame K. The treatment used includes collision effects and makes no assumptions about the relative and absolute values of the velocity components. The formula obtained is compared with the corresponding one for a reference frame K' in which the particle's orbit is at rest. A spread in velocities for an assembly of particles is then taken into account, and formulas are derived for a relativistic Maxwell distribution. It is finally shown that, in the nonrelativistic limit, the well-known Voigt profile is obtained for the one remaining cyclotron line.

C8. Angular and Frequency Dependence of Plasma Synchrotron Emission. DAVID B. BEARD, *University of California.*—Several authors[1-3] have demonstrated that, for frequencies greater than the plasma frequency, one may treat the plasma synchrotron emission by integrating the emission from each separate electron over all the electrons in the plasma unless blackbody surface brightness is exceeded. Drummond and Rosenbluth[3] based part of their discussion on a brief notice[2] containing a consequential error in the sign of an arctangent rather than on the complete account[2] which was known to be correct. Subsequently, Trubnikov[1] has criticized Drummond and Rosenbluth's work, correcting their assumption that he had ignored the emission's angular dependence and giving what Trubnikov believed to be a more accurate estimate of the angular dependence. The angular and frequency dependence of the emission have been further approximated and compared with other estimates[1-3] and numerical calculations. *Drummond and Rosenbluth's[3] angular approximation was found to be exceptionally good.*

[1] B. A. Trubnikov and V. S. Kudryavtsev, 1958 Geneva Conference and Phys. Fluids 4, 195 (1961).
[2] D. B. Beard, Phys. Rev. Letters 2, 81 (1959), and Phys. Fluids 2, 379 (1959).
[3] W. E. Drummond and M. N. Rosenbluth, Phys. Fluids 3, 45 (1960).

C9. Numerical Calculation of Plasma Synchrotron Emission.* JOHN C. BAKER AND DAVID B. BEARD, *University of California.*—In Sherwood plasmas the plasma frequency (for which the index of refraction can be immense) is less than the harmonic frequencies where most energy loss occurs; hence no sharp changes in refractive index occur, and the emission as a function of frequency and angle may be studied by computing the emission from individual electrons. The results of exact numerical calculations of the frequency and angular dependence of microwave emission by a Maxwell-Boltzmann velocity distribution of energetic electrons will be presented as a function of temperature as will the consequences of this emission for various plasma dimensions. Trubnikov and Kudryavtsev[1] and Drummond and Rosenbluth[3] have emphasized the distortion of the Maxwell-Boltzmann distribution due to the radiation energy loss. Aside from the insight to be gained into the general behavior of the emission and the validity of the approximations, however, the results may be applied to any roughly exponentially decreasing velocity distribution. Although trivial, wall reflections[1-3] have not been included.

* Supported by the U. S. Atomic Energy Commission.
[1] B. A. Trubnikov and V. S. Kudryavtsev, 1958 Geneva Conference (Pergamon Press).
[2] W. E. Drummond and M. N. Rosenbluth, Phys. Fluids 3, 45 (1960).
[3] D. B. Beard, Phys. Fluids 2, 379 (1959).

C10. The Two-Way Heat Equation.* M. KRUSKAL, *Project Matterhorn, Princeton University.*—In his researches on probe theory, I. B. Bernstein was led to consider a partial differential equation of parabolic type in which the "time" variable flows in opposite directions in different regions of the "space" variable. A simple prototype of this equation is $k(x)u_t = u_{xx}$, with $sgn(k(x)) = sgn(x)$. The results of studying this equation in specially simple domains and with specially simple choices for $k(x)$ indicate that the natural well-posed problem consists, as would be expected, of presecibing arbitrary "initial" values of u for the smallest value of t at each $x>0$ and for the largest at each $x<0$. Integral representations of the solution are obtained in two cases. The first is in the half-plane $t>0$ with $k(x) = |x|^{\alpha} sgn(x)$. The second is in the infinite strip $0<t<1$ with $k(x) = sgn(x)$. Both cases are reduced to integral equations (by different methods), which are then solved by taking appropriate integral transforms. Some uniqueness theorems are also proved, by adaptation of standard methods for the heat equation.

* Work accomplished under the auspices of U. S. Atomic Energy Commission.

C11. How Much Does an Adiabatic Invariant Vary?* O. BUNEMAN, *Stanford Electronics Laboratories.*—The adiabatic invariance of the moment of a particle orbit (transverse energy/magnetic field) can be proved to all orders of a parameter ϵ which measures the relative rate of change of the field. However, particle motion can be calculated accurately in an axisymmetric field whose pressure changes from one value to another like $[\text{const} \pm \tanh(\pi\epsilon t).]$. The moment then increases by the factor

$$[1-\exp(-\bar{\Omega}/\epsilon)][1-\exp(-\Omega_1/\epsilon)]^{-1}[1-\exp(-\Omega_2/\epsilon)]^{-1},$$

where Ω_1 and Ω_2 are the initial and final gyrofrequencies, $\bar{\Omega}$ their mean. Likewise when the field pressure returns to its original value after passing through a maximum or minimum like $[\text{const} \pm \text{than}^2 \pi\epsilon t]$, an energy increase is calculated. When $\epsilon \to 0$ these increases approach zero nonanalytically; hence the misleading result of the calculation in orders (powers) of ϵ. The energy increases enhance the Fermi mechanism.

* Supported by U. S. Air Force contract.

Properties of Plasmas

D1. Rotating Probe Measurements in the Interior of the P-4 Steady-State Plasma.* A. L. GARDNER AND N. L. OLESON,† *Lawrence Radiation Laboratory.*—Measurements using stationary tungsten probes in the outer regions of the steady-state plasma of the P-4 system[1] were described earlier.[2] The heating by the highly ionized plasma precludes the use of such

probes in the interior. A rotating probe mechanism has been built and used for measurements all the way into the axis of the plasma. From analysis of positive currents to the probe a value of the ion density on the axis of approximately 1.5×10^{13} per cc is obtained in reasonable agreement with microwave measurements.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† U. S. Naval Postgraduate School, Monterey, California.
[1] A. L. Gardner, L. S. Hall, and D. E. Edwards, Bull. Am. Phys. Soc. Ser. II, 5, 313 (1960).
[2] Footnote 1, N. L. Oleson and D. M. Gall.

D2. Double-Probe Measurements of Electron Temperature in a Plasma Stream. M. A. GILLEO, *Lockheed Missiles and Space Division.*—The double-Langmuir-probe method of Johnson and Malter has been used successfully for the determination of electron temperature and positive-ion number density in a high-speed (7.10^6 cm/sec) stream of plasma. The plasma was produced by a coaxial gun which fires into a tube evacuated to a pressure of about 2.10^{-6} mm. Hydrogen was admitted to the gun in a pulse of approximately 80-μsec duration. Bursts of plasma from the gun were guided to the probe more than a meter away by an axial magnetic field of 2000 gauss. At this distance an electron temperature of 3 ± 0.3 ev and an ion density of about $2\cdot10^{12}$ cm^{-3} were observed. At points closer to the gun the electron temperature and plasma density were higher. Spectroscopic data indicated a probable ion temperature of a few tenths of an ev so that the thermal energy of the ions is less than 1% of their translational kinetic energy. These diagnostic measurements were carried out in conjunction with an experiment on the encounter of a plasma stream with a magnetic barrier.[1]

[1] M. A. Gilleo, Bull. Am. Phys. Soc. Ser. II, 5, 326 (1960).

D3. Measurements on a Cesium Plasma.* M. A. ALLEN, G. S. KINO, AND J. D. LAWSON,† *Microwave Laboratory, W. W. Hansen Laboratories of Physics, Stanford University.*—A plasma has been found with positive ions being produced by conversion of cesium atoms to cesium ions at tungsten surfaces and electrons being produced by thermionic emission from the same surfaces. Plasma densities of over 10^{11}/cc have been measured in columns 25 cm long. Low-frequency impedance measurements of the columns yield impedance within a factor of two of the Spitzer-Härm values for a fully ionized plasma. External capacitative probe measurements show that fluctuations occur within the plasma columns, mainly in the range of 10 kc to 100 kc.

* Supported by Air Force Research Division, Air Research and Development Command.
† On leave from Atomic Energy Research Establishment, Harwell, England.

D4. Diffusion of a Low-Temperature, Highly Ionized Cesium Plasma across a Magnetic Field.* N. RYNN AND N. D'ANGELO, *Project Matterhorn, Princeton University.*—A steady-state, highly ionized, low-temperature cesium plasma has been produced in a longitudinal magnetic field. A theoretical analysis of the plasma has been made and measurements of radial profiles have been taken at densities of the order of 10^{12}/cm^3, with the confining field varying from 2000 to 6500 gauss, and a plasma temperature of 1900°K. The results of the measurements will be presented, and the dependence of the radial density profile upon magnetic field will be discussed. Preliminary indications are of a $1/B^2$ dependence of the diffusion coefficient on the magnetic field.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

D5. Measurement of α/p for H_2 across a Strong Magnetic Field. MELVIN J. BERNSTEIN. *Lawrence Radiation Laboratory.*—The ionization coefficient α/p of hydrogen was measured with a steady magnetic field applied perpendicular to the electric field. The experiment was done in a cylindrical geometry to avoid any problems due to $E\times B$ electron drift. At a given E, p, B the anode current was plotted as a function of gap separation to yield α/p. Blevin and Hayden[1] have derived a theory of how α/p should vary with magnetic field. Their theory is based on the fact that in hydrogen the collision frequency of electrons is almost independent of energy. They use the parameter $\omega\tau$, where ω is the electron cyclotron frequency and $1/\tau$ is the collision frequency. The empirical formula (for $B=0$) $\alpha/p=A\exp(-Cp/E)$ is used (A and C are constants); this form is shown by Rose[2] to be sufficiently accurate. Their result is $\alpha/p=A[1+(\omega\tau)^2]^{\frac{1}{2}}\exp\{-C(p/E)[1+(\omega\tau)^2]^{\frac{1}{2}}\}$. This experiment was done with B varied up to 8000 gauss, and covered the pressure range of 1 to 8 mm Hg. Values of $\omega\tau$ ranged up to 10. Diffusion of electrons along magnetic field precluded using values of $\omega\tau$ appreciably higher than 10. The experimental values of α/p approximately follow the theory but are observed to be smaller in magnitude than theory.

[1] Blevin and Hayden, Australian J. Phys. 11, 18 (1958).
[2] D. J. Rose, Phys. Rev. 104, 273 (1956).

D6. Ionic Mobility in Shock-Heated Xenon.* PER GLOERSEN, *General Electric Space Sciences Laboratory.*—A recently described[1] $v\times B$ probe technique has been applied to the plasma created behind a shock wave in xenon.[2] A 10^4-ohm load resistor across the probes gave rise to voltage signals starting suddenly at the shock front and continuing with almost constant amplitude to the trailing edge of the delayed luminous region.[2] A 10^4-ohm resistor produced lower voltages, with time contours closely paralleling those of the delayed luminosity. These measurements were combined to obtain plasma resistances, which are compared to previous values obtained in hydrogen.[1] In addition, ionic mobilities were calculated, assuming equilibrium ionization of the xenon at the point of maximum luminosity and probe voltage to obtain an upper limit on the number of xenon ions present. The values of mobilities so obtained are much larger than would seem reasonable by extrapolation of mobility values obtained at room temperatures, suggesting that perhaps the "resistance" of the plasma may be determined largely by the rate at which electrons are ejected from the cathode probe surface by metastable and/or photoelectric action.[2]

* Based on work performed under the auspices of the U. S. Air Force, BMD.
[1] M. Sakuntala, A. von Engel, and R. G. Fowler, Phys. Rev. 118, 1459 (1960).
[2] P. Gloersen, Phys. Fluids 3, 857 (1960).

D7. Measurements of Thermal Conductivity in a Magnetoplasma.* F. M. ROSTAS AND J. H. CAHN, *University of Illinois.*—Preliminary determinations have been made of the thermal conductivity of a long narrow plasma ($n=10^{13}$/cm^3, Ne gas at 7 mm Hg) in a transverse magnetic field of the order of 1000 gauss. As in earlier work,[1] use is made of the high degree of decoupling between the electrons and the heavy constituents of the plasma. The electrons are heated locally in a very small region by microwave techniques. Afterglow quenching is used to detect and measure the variation of the electron temperature, and microwave measurements determine the number density and collision frequency of the electron gas in magnetic fields well below the cyclotron resonance field. The results are compared to theory.

* Work supported in part by U. S. Air Force Cambridge Research Center.
[1] L. Goldstein and T. Sekiguchi, Phys. Rev. 109, 625 (1958); T. Sekiguchi and R. C. Herndon, Phys. Rev. 112, 1 (1958).

D8. Hydromagnetic Waves in a Magnetically Stabilized Arc Column. C. K. MCLANE, *Speedway Research Laboratory, Linde Company, Division of Union Carbide Corporation.*—Waves which occur in the column of a magnetically stabilized

low-pressure argon arc have phase velocity proportional to magnetic field and decay time inversely proportional to square of wave number. These characteristics, reminiscent of hydromagnetic waves, occur in spite of the fact that the ion cyclotron frequency is lower than the oscillation frequency. Electrostatic coupling between ions and electrons, which will be strong because of boundary effects in the thin (3-mm) column used in this work, may provide the explanation for this behavior. It has been found possible to excite oscillations very near the frequency at which they occur naturally by applying a transverse, radio-frequency electric field to the discharge. Attempts to excite column oscillations by application of a radial electric field have not been successful. These observations suggest that what is being observed is an $m=1$ mode in which the free column moves like a plucked string.

D9. Beam Plasma Interaction. C. ETIEVANT, *Service de Recherches sur la Fusion Contrôlée, Centre d'Etudes Nucléaires de Fontenay-aux-Roses, France.*—Waves excited in a plasma by an electron beam are experimentally studied in the presence of a magnetic field (1.500 gauss). The plasma is produced by a PIG discharge in hydrogen or helium. The period of interest occurs during the decay of the plasma after the discharge has been short-circuited by an ignitron. Microwave measurements with an interferometer (8-mm) show that the electron density in H_2 decreases from $n_e=4.10^{11}$ el/cm^3 to $n_e=10^{11}$ el/cm^3 in a time of the order of 50 μsec. The measurements give evidence that the plasma is much less turbulent during the decay than during the PIG discharge. The gun produces a uniform flow of electrons (10 kev $-$ 1A) parallel to the magnetic field. The beam (1-cm diameter) is injected into the discharge through one cathode and is collected after passing through the other cathode. Oscillations are detected by magnetic and Langmuir probes in the plasma and by measurements of the modulation of the collected beam.

D10. Experimental Observations of Hydromagnetic Wave Modes and Reflections. ALAN W. DESILVA, WILLIAM S. COOPER, III, AND JOHN M. WILCOX, *Lawrence Radiation Laboratory.*—A hydrogen plasma (5×10^{13} ions/cm^3) is produced in a cylindrical tube in an axial magnetic field of 15 kgauss. A torsional hydromagnetic wave[1] is induced at one end of the tube, and the radial dependence of the wave magnetic field b_θ is measured by means of magnetic probes at the other end. The wave drive is coaxial, and it is experimentally verified that the wave consists principally of $m=0$ modes. Although the tube in which the plasma is contained is a good conductor, it is found that the boundary condition at the tube wall is such that the radial current there is zero. The dominant mode observed is the lowest theoretically predicted principal mode.[2] Reflections of these waves eight times between the insulating end boundaries also have been observed, E reflecting in phase and b_θ reflecting out of phase, corresponding to predictions for a high-impedance boundary.

[1] M. Wilcox, F. I. Boley, and A. W. DeSilva, Phys. Fluids 3, 15 (1960).
[2] W. A. Newcombe, in *Magnetohydrodynamics* (Stanford University Press, Stanford, California, 1957), p. 109.

D11. Frequency Spectra of Low-Frequency Fluctuations in a Plasma.* F. W. CRAWFORD, *Microwave Laboratory, W. W. Hansen Laboratories of Physics, Stanford University.*—Observations have been made of the low-frequency fluctuations occurring in hot-cathode, dc, mercury-vapor discharges at a pressure of ~1 μ. A spectrum analyzer was employed to study frequency spectra from three widely differing experimental tubes and to determine the effects of variations in tube geometry, electrode spacing, and anode current. Similar measurements also were made at points along a long discharge column with the aid of a capacitive probe sliding on the outside of the tube. The character of the spectrum is markedly dependent on tube geometry, substantially independent of column length and position along the column, and may be coarse or contain relatively pure frequency components. One mechanism observed involved frequency variation proportional to the square root of the anode current, and a possible explanation is given. There is, however, evidence for the existence of other basic mechanism of generation.

* Work supported by U. S. Atomic Energy Commission contract.

D12. Spectroscopic Investigations of Doppler Effects in a Luce Type Carbon Arc. P. M. GRIFFIN AND G. K. WERNER, *Oak Ridge National Laboratory.**—The magnetically confined, low-pressure, high-current carbon arc exhibits many unusual properties as observed by optical spectroscopy. Unusually broad and Doppler-shifted spectrum lines from carbon ions in such an arc have been reported previously.[1] Extensive quantitative measurements of these two phenomena as they are affected by arc current, background pressure, and magnetic field strength recently have been made and are reported in this paper. The half-intensity width of the C^{++} $\lambda4647$ A line decreased linearly from 0.651 to 0.345 A as the arc current was increased from 150 to 450 amp. However, the background pressure increased from 1.0×10^{-5} to 1.6×10^{-4} mm of Hg as a result of this increase in current. In fact, the linewidth can be described quite well by the relation $w=61p^{-1/3}$ where w is the half intensity width in mA and p is the background pressure in mm of Hg. As the arc current is increased beyond 450 amp, the line width tends to increase. Although no detailed description of ion motions in the arc are implied, the Doppler shifted wavelengths of the light from different zones in the arc as viewed perpendicular to the arc are consistent with the concept of an azimuthal precession of the ions about the arc axis in a sense opposite to that of the Larmor rotation. This precession frequency increases from 90 to 180 kc/sec as the arc current is increased from 150 to 450 amp with a dip in the curve at 400 amp. The Larmor frequency for the C^{++} ion under these same conditions is 665 kc/sec.

* Operated by Union Carbide Nuclear Company for the U. S. Atomic Energy Commission.
[1] J. R. McNally, Jr. and M. R. Skidmore, J. Opt. Soc. Am. 47, 863 (1957); J. R. McNally, Jr., *ibid.* 49, 328 (1959).

D13. Impedance Characteristics of a Low-Pressure Mercury-Vapor Plasma.* F. W. CRAWFORD, *Microwave Laboratory, W. W. Hansen Laboratories of Physics, Stanford University.*—Measurements have been made of the impedance/frequency characteristics of a hot-cathode, dc, mercury-vapor plasma at a pressure of ~1 μ. The experimental tube contained an indirectly heated cathode from a commercial mercury-vapor rectifier and provided a discharge column ~75 cm long. Bridge techniques were used to obtain impedance loci extending to ~1.5 Mc/sec, for several values of anode current. These were found to normalize, the magnitudes of the components being inversely proportional to current. A basic equivalent circuit can be deduced, its parameters being related to the physical processes occurring in the discharge.

* Work supported by Atomic Energy Commission contract.

Stability Theory and Waves in Plasma

E1. Conditions for the Existence of a Static "Triax" Pinch. ELI RESHOTKO, *NASA Lewis Research Center* (introduced by W. E. Moeckel).—For an isothermal plasma having a scalar electric conductivity, an analysis shows that a static Triax configuration is possible only when less than half the total current is passed through the central core. Containment is

here attributed to a B_θ field which changes sign in the plasma and, in fact, the maximum particle density occurs at the B_θ null point. A necessary condition for stability in the limiting case of an inviscid, infinitely conducting plasma[1] is satisfied for this configuration with very modest externally imposed B_z fields.

[1] B. R. Suydam, *Proceedings of the Second United Nations Conference on the Peaceful Uses of Atomic Energy* (United Nations, Geneva, 1958), Vol. 31, P/354, p. 157.

E2. Thermal Convection in the Slow Pinch Discharge.* A. A. WARE,† *General Atomic.*‡—In an earlier paper[1] the theoretical magnetohydrodynamic stability of a slow pinch discharge (having constant pitch magnetic field) was considered. Comparison with experiment suggested that only the interchange modes occur in practice, the observed pressure gradient being in close agreement with the theoretical limit $d\ln p/dr=\gamma d\ln B_z/dr$. When the Hall emf is retained in the electric conduction equation, other slower growing instabilities are found which result in thermal convection.[2] In this paper these thermal instabilities are considered in relation to the temperature gradients and heat losses from the slow pinch discharge.

* Research on controlled thermonuclear reactions is a joint program of General Atomic and the Texas Atomic Energy Research Foundation.
† On leave of absence from Associated Electrical Industries Research Laboratory, Aldermaston, Berkshire, United Kingdom.
‡ John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic Division of General Dynamics Corporation, San Diego, California.
[1] A. A. Ware, Gaseous Electronics Conference, Monterey, 1960.
[2] P. Gloersen, Phys. Fluids **3**, 875 (1960).

E3. Sheet Pinch Instabilities Caused by Finite Conductivity.* H. P. FURTH, *Lawrence Radiation Laboratory, Livermore, California.*—How hydromagnetic stability can be impaired by finite resistivity is illustrated by the case of a sheet pinch in the xz plane, with B_y, $B_z=0$, and B_x changing from $+B$ to $-B$ as one passes from large positive to large negative values of y. Starting with a perturbation $\xi_y(y)e^{ikx}$, where ξ_y is an odd function of y, magnetic field diffusion leads to nonzero values of B_y even for $y=0$. For small k, there result $\mathbf{E}_z\times\mathbf{B}_y$ motions in the x direction, such as to "shred" the sheet pinch into streamers. These concepts have been developed qualitatively in an astrophysical context by Dungey.[1] From the point of view of experimental plasma physics, they are particularly relevant to "hard-core" pinches.[2] By allowing finite B_z, the treatment can be generalized to current layers across which B rotates by less than 180°. Thus a sheet pinch resembling the surface of a "stabilized pinch" is subject to shredding along helical lines. This effect has been demonstrated by S. A. Colgate *et al.*, using sodium tubes. The usefulness of the shredding instability in the design of plasma accelerators[3] is discussed briefly.

* This work was done under the auspices of the U. S. Atomic Energy Commission.
[1] J. W. Dungey, *Cosmic Electrodynamics* (Cambridge University Press Cambridge, 1958), pp. 98–102.
[2] S. A. Colgate and H. P. Furth, Phys. Fluids **3**, 982 (1960).
[3] H. P. Furth, "An instability-type plasma accelerator," UCRL-6118-T (August, 1960).

E4. Stability of Axially Symmetric Equilibria. C. MERCIER AND M. COTSAFTIS, *Association Euratom-CEA, Fontenay-aux-Roses.*—A necessary condition for the stability of axially symmetric equilibria has been derived from the energy principle by considering displacements which are localized in the neighborhood of those constant pressure surfaces on which the magnetic lines of force are closed.[1] The criterion was applied numerically to a number of examples. The most severe condition was obtained every time by applying the criterion in the neighborhood of the magnetic axis. In fact the resulting condition near the magnetic axis can be obtained analytically for the most general equilibrium. It turns out to be especially simple when the constant pressure curves in a meridian plane are circles near the magnetic axis. If τ is the "rotational transform angle" the condition for stability is: $\tau<2\pi$ or $\tau>2\pi$ according as the pressure has a maximum or a minimum on the magnetic axis. If R, j, and B are the radius, current density, and magnetic field, $\tau=4\pi^2Rj/B$.

[1] C. Mercier, in Nuclear Fusion (International Atomic Energy Agency) (to be published).

E5. Hydromagnetic Stability of Toroidal Systems.* JOHN L. JOHNSON† AND JOHN M. GREENE, *Project Matterhorn, Princeton University.*—The hydromagnetic stability of toroidal equilibria in which plasma is contained by a strong magnetic field, parallel to the center line of the torus, with superposed multipolar fields, is studied by means of the energy principle.[1] The equilibrium configurations have been obtained by an expansion technique in which the amplitude of the multipolar field, the plasma pressure, the currents, and the effect of curvature are assumed small compared to the main field.[2] Following the techniques developed to determine the stability of linear systems dominated by a uniform field[3] the potential energy variation is obtained as a functional of a divergence free displacement vector which lies in the plane of a cross section of the torus and depends only on the two coordinates which describe this plane. A necessary condition for stability against displacements localized in a region where they are nearly constant along field lines is obtained in terms of the eignevalues of an infinite matrix. This has been applied to several cases.

* Work accomplished under the auspices of the U. S. Atomic Energy Commission.
† On loan from Westinghouse Electric Corporation, Atomic Power Department.
[1] I. B. Bernstein, E. A. Frieman, M. D. Kruskal, and R. M. Kulsrud, Proc. Roy. Soc. (London) **A244**, 17 (1958).
[2] J. M. Greene and J. L. Johnson, Bull. Am. Phys. Soc. Ser. II, **5**, 312 (1960).
[3] J. L. Johnson, C. R. Oberman, R. M. Kulsrud, and E. A. Frieman, Phys. Fluids **1**, 281 (1958).

E6. A Computational Program for Helically Invariant Hydromagnetic Systems.* J. M. GREENE, J. L. JOHNSON,† M. D. KRUSKAL, J. R. PESKIN, AND L. WILETS,‡ *Project Matterhorn, Princeton University.*—In accordance with a previously developed energy principle for hydromagnetic equilibria,[1] we have prepared a Fortran program (for the IBM 704 computer) designed to decrease systematically the energy of a hydromagnetic system by successfully moving each fluid element of a discrete approximant to the position where it is in equilibrium with its immediate neighbors. The most general three-dimensional situations which can be treated as two-dimensional are allowed for, namely those with helical invariance (i.e., "screw" symmetry). It is planned to use this program not only to find helical equilibria, but also to investigate the stability of cylindrically symmetric equilibria against helical perturbations. At present the code is completely written and performs as expected in simple test runs.

* Work accomplished under the auspices of U. S. Atomic Energy Commission.
† On loan from Westinghouse Electric Corporation, Atomic Power Department.
‡ University of Washington.
[1] M. Kruskal and R. Kulsrud, Phys. Fluids **1**, 265 (1958).

E7. Angular Momentum Criteria for Plasma Stability. WILLIAM I. LINLOR, *Hughes Research Laboratories.*—Dense plasmas confined by magnetic fields may become unstable when heated because of rotational motion of the plasma. If the angular momentum with respect to guiding centers,

$$J_p\left(=\int_0^r [4\pi rn/Be][m_ikT_i-m_ekT_e]dr\right),$$

increases because of heating, it must be counterbalanced by drift angular momentum of the plasma,

$$J_d\left(=\int_0^r 2\pi r^2n[m_i+m_e][\mathbf{E}\times\mathbf{B}/B^2]dr\right),$$

plus electromagnetic angular momentum,

$$J_m\left(=\int_0^r 2\pi r^2[\mathbf{E}\times\mathbf{B}/4\pi C^2]dr\right).$$

Drift motion shields the interior of a dense plasma. Hence J_p must be counterbalanced by J_d and J_m in the region where a radial electric field exists, producing large azimuthal velocity and consequent streaming instability. Stable situations are expected if angular momentum is supplied from external sources, or if heating occurs by adiabatic compression which does not change J_p, or regardless of the heating method in dilute plasmas ($n_i < 100B^2$).

[1] L. Spitzer, Jr. *Physics of Fully Ionized Gases*, notation as on p. 99.

E8. Excitation of Plasma Waves by Bodies Moving in Ionized Atmosphere. K. P. CHOPRA, *Polytechnic Institute of Brooklyn.*—A body moving in an ionized atmosphere acquires an electric charge through the processes of accretion of charged particles and emission of electrons by high-energy photons. The moving charged body may then interact with the charged particles of the atmosphere and any pervading magnetic field to excite plasma waves. The paper describes mechanisms which, under suitable circumstances, produce electrostatic, electromagnetic, and magnetohydrodynamic modes. The el electrostatic waves are characterized by the longitudinal oscillations of ions or electrons and are produced by the long-range Coulomb interaction between the charged body and the charged particles. The extraordinary electromagnetic waves result from the interaction of the charged body with the charged particles gyrating around the magnetic lines of force. In the third mechanism, the rapidly moving body carrying an electric charge arrests an ionized cloud in front of it. The motion of this ion cloud induces an instability in the atmosphere and causes a column of ionized gas to move ahead of the body. The magnetic field interacts with this ionized column to produce magnetohydrodynamic waves.

E9. Recombination of Ions and Electrons.* N. D'ANGELO, *Project Matterhorn, Princeton University.*—A process of electron-ion recombination is considered, involving three bodies (one ion and two electrons), in which an electron, as a result of a collision with another electron, loses enough energy to be captured in one of the excited electronic orbits of the ion and then ends in the ground state by emission of one or more light quanta. It is shown that such a process might account for the large values of the recombination coefficient found experimentally.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

E10. Conductivity Values for Any Degree of Ionization Based on a Maxwellian Distribution. I. P. SHKAROFSKY, *RCA Victor Research Laboratories.*—Values are presented for the conductivity for any degree of ionization, radio-frequency, and dc magnetic field strength and various electron speed power law variations of the electron collision frequency with neutral particles. The analysis is based on substitution of the usual series expansion of Laguerre polynomials into the Fokker-Planck equation. For electron-electron effects, the expressions are the same as those of Landshoff. Collisions of electrons with neutral particles are included in addition to ions, and ac electric fields are treated as well as dc magnetic fields. The final conductivity results can be put in a form which yield two factors, multiplying respectively the average collision frequency and radian frequency to give correct results from the simple equations. These factors are of order one and are function of three parameters, proportional to angular frequency, ratio of electron-neutral to ion averaged collision frequency, and ion charge numbers. Plots are shown for various conditions of interest.

E11. On Some Particular Cases of the Propagation of Disturbances in Ionized Gases.* M. Z. v. KRZYWOBLOCKI, *Michigan State University.*—The work is concerned with some particular cases of the propagation of disturbances in ionized gases. Three types of waves are discussed: electromagnetic-, electrostatic-like, and combined waves. In some cases only the dependence upon two dimensions (x, t) is taken into account. Various subcases referring to the three types of wave propagation, mentioned above, take into account some simplifications like: (a) isentropic conditions of the hydrodynamic aspects of the flow system; (b) small perturbations; (c) dependence upon one coordinate of the position and the time t; (d) dependence upon more than one coordinate of the position and the time t, etc.

* The work was sponsored by the Research Department, Martin-Denver Company, Denver, Colorado, with Dr. W. Clohessy as its Director.

E12. S and P Wave Coupling in a Hydromagnetic System. GIRARD R. LOWREY, JR., *Aero Geo Astro Corporation*, AND ROGER C. JONES, *Melpar, Incorporated.*—In an ionized gas immersed in a magnetic field, a low-frequency sound wave termed the S wave can exist. This magnetic sound wave interacts with a high-frequency plasma wave by means of electron-ion collision processes, or (more generally) electrical-ion-neutral collision processes. An analysis is presented of S-P wave coupling in which the collision processes appear in terms of unknown parameters. Thus, by using the theory presented here and appropriate experiments, the magnitude of the various collision cross sections can be determined. Conversely, if these cross sections are adequately known, the P wave modulation due to S wave coupling can be predicted.

Mirrors and Cusps

F1. Trajectories of Ions Injected into a Magnetic Mirror Configuration. C. GOURDON, *Centre d'Etudes Nucléaires de Fontenay-aux-Roses, France.*—We study molecular ion injection into systems presenting a symmetry of revolution. Dissociation upon an axial arc assures capture of the dissociated ions. We systematically search for injection conditions leading to trajectories having multiples passes through the axis. One can show the possibility of such trajectories even in the presence of an axially symmetric space charge potential. In certain cases, the dissociated ions are absolutely confined, neglecting interactions. Specific trajectory calculations have been effected on a digital computer. The particles are assumed to be injected in the median plane, with a small axial component of velocity. We have envisaged two cases: (1) The canonical angular momentum p_θ equals zero. In this case the particles rigorously pass through the axis. The number of revolutions is limited to less than one hundred. (2) p_θ slightly negative. In this case, the particle circles the axis but remains near to cross the arc. One can then obtain the mirrors closed to the molecular ions and find more than 100 revolutions. An experimental study of this problem is under way by means of an electron model.

F2. Trapping and Confinement of 20-kev Hydrogen Atoms in a Magnetic Mirror Machine.* J. F. STEINHAUS AND C. C. DAMM, *Lawrence Radiation Laboratory.*—A beam of hydrogen

atoms of 20-kev energy and 1.5-ma equivalent intensity was injected diametrically across the midplane of a magnetic mirror machine. The major trapping mechanism is ionization by impact with residual gas molecules while the controlling loss process is charge-exchange neutralization of the protons by collision with the gas. The energetic atom beam was formed by neutralization of a proton beam in a hydrogen gas cell at a net measured efficiency of 0.70. The trapped ion density was estimated from the measured beam intensity by comparison of the ion trapping and loss rates, yielding a value of 8×10^{5} ions/cm³. The Debye length at this density is comparable to the machine dimensions (21-cm diameter) so that essentially single-particle behavior was observed. The characteristic build-up and decay times for the trapped ion density were measured in the pressure range from 3×10^{-5} mm Hg to 3×10^{-6} mm Hg and agree with the values predicted from the charge-exchange cross section within experimental uncertainty. The decay times measured were independent of magnetic field intensity, and hence orbit size, within the range from 2.5- to 5-cm orbit diameter. We conclude that losses due to nonadiabatic particle trajectories are negligible under these conditions.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

F3. Ion Heating by Alternating Radial Electric Field in a Mirror Machine.* E. S. CHAMBERS, *Lawrence Radiation Laboratory.*—An alternating radial electric field was applied to one end of a hollow cylindrical plasma in a magnetic mirror.[1] Energy was propagated to an ion cyclotron resonance region within the machine and there heated ions. This method of introducing radio-frequency energy at the end of a mirror machine was proposed by H. P. Furth. Driving point impedance increased with rf electric field (order of 60 v/cm). However the impedance rose sharply when the rf field was reduced below a certain point, with a minimum of 1.6 ohms. Both impedance and phase velocity were insensitive to static magnetic field and neutral density. These results do not fit into the simple hydromagnetic picture and suggest the predominance of an rf sheath. Hot ions, collected on a shielded, positively biased (300-v) electrode had a current density of 100 μA/cm². Some positive current was still obtained with a 600-v bias. The spatial distribution of hot ions was studied by discoloration patterns on a copper strip and by a hot-neutral "camera."

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] E. Chambers and H. P. Furth, Bull. Am. Phys. Soc. Ser. II, 5, 310 (1960).

F4. Plasma Calorimetry in the Table Top Mirror Machine.* T. O. PASSELL,† *Lawrence Radiation Laboratory.*—Integrating, thermistor-sensed calorimeters have been used for measuring the total energy of the compressed plasma of a Mirror Machine.[1] The high sensitivity (<5 millijoules/cm²) obtained using a thermistor itself as the calorimeter allowed detection of plasma escaping across the magnetic field as well as that escaping axially (parallel to B). The results obtained calorimetrically generally confirm those already obtained from scintillation detectors.[2] The calorimeter thermal time constant ($\sqrt{2}100$ sec) allowed our monitoring up to 12 separate calorimeters on a chart recorder. Absolute energies obtained by intercepting all the escaping plasma (except that returning to the plasma source located on the magnetic axis) were combined with the known energy distribution[3] and total volume to give an approximate plasma density. Eddy current heat for peak fields of 6–10 kgauss at the calorimeter was seldom >10% of plasma heat so long as materials such as graphite cloth or the thermistor body itself constituted the body material.

* Work done under the auspices of the U. S. Atomic Energy Commission.
† Stanford Research Institute, Menlo Park, California.
[1] R. F. Post, R. E. Ellis, F. C. Ford, and M. N. Rosenbluth, Phys. Rev. Letters 4, 166 (1960).
[2] W. A. Perkins and R. F. Post, Bull. Am. Phys. Soc. Ser. II, 5, 353 (1960).
[3] R. E. Ellis, W. A. Perkins, and R. F. Post, Bull. Am. Phys. Soc. Ser. II, 5, 309 (1960).

F5. Ion Energy Distributions in Magnetically Compressed Plasmas.* F. H. COENSGEN, W. F. CUMMINS, W. E. NEXSEN, JR., AND A. E. SHERMAN, *Lawrence Radiation Laboratory.*—Plasma has been trapped in a magnetic field between dc and pulsed magnetic mirrors. After trapping, the plasma was radially compressed by increasing the field. At the end of the compression the magnetic field between the mirrors exceeded that of the dc mirror but was lower than that of the pulsed mirror. The plasma thus was permitted to escape into an ion energy analyzer beyond the dc mirror. The operation of this experiment is similar to that in the first stage of a multistage magnetic compression experiment[1] reported previously. However, in the present experiments the initial ion rotational energies can be a factor of 100 greater than those in the previous experiment as the trapping fields are a factor of 10 greater. The plasma generators and the ion energy analyzer are similar to those described in the multistage paper. For a plasma in which the initial density was of the order of 10^{13} ions/cm³, the average energy was found to be increased about 400 ev for an effective compression of 17. Integration over the energy distribution indicates that over 40% of the injected D^+ ions were trapped and compressed.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] F. H. Coensgen, W. F. Cummins, and A. E. Sherman, Phys. Fluids 2, 350 (1959).

F6. Injection and Trapping at High β in a Picket Fence Geometry.* J. E. OSHER AND D. C. HAGERMAN, *Los Alamos Scientific Laboratory.*—Experiments using a coaxial hydromagnetic gun[1] to inject plasma[2] into a picket fence confinement geometry show that a $\beta\approx1$ region can be injected through the magnetic entrance cusp and produce a trapped $\beta\approx1$ region within the picket fence volume. Experimentally a plasma jet having a mean deuteron kinetic energy of 1 kev and a number density of $\sim5\times10^{13}$/cm³ is able to penetrate cusp fields $\lesssim$2000 gauss as a $\beta\approx1$ region, but for fields >2000 gauss $\beta<1$ since the electron density is too low to support the sheath current. For 1200-gauss cusp fields this plasma jet opens the entrance cusp for 3 μsec, builds up a $\beta\approx1$ region within the picket fence, and then this diamagnetic signal decays with $\tau\approx40$ μsec. Measurements indicate that only the low-energy component of the injected plasma is trapped in the biconical $\beta\approx1$ region. For 300-gauss cusped field this region has a length of 20 cm, maximum diameter of 12 cm, and is bounded by a sheath several cm thick. Radial and axial oscillations (10-μsec period) of the entire trapped plasma are observed. The energy spectrum of escaping particles will be discussed.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] J. E. Osher and D. C. Hagerman, Bull. Am. Phys. Soc. Ser. II, 5, 350 (1960).
[2] J. L. Tuck, Phys. Rev. Letters 3, 313 (1959).

F7. Plasma Injection Experiments in an Isolated Cusp Magnetic Field.* F. R. SCOTT AND H. G. VOORHIES, *General Atomic.*†—In order to minimize the effects of walls on injection and containment in a "Magnetic Bottle," a system has been constructed which permits the field producing coils to be placed in the evacuated chamber. By using a previously reported conical tube and fast gas valve as a plasma injector, the mean radius of the plasma and plasma-field boundary layer have been measured as a function of field strength at the injection throat of this isolated cusp. A complete diamagnetic

effect in deuterium was observed up to 3100 gauss. From 1100 to 3100 gauss the mean radius was twice the cyclotron radius of deuteron with a velocity of 8.6×10^6 cm/sec. This is the measured initial average axial velocity of the injected plasma. Data on deuterium, helium, and hydrogen will be given showing the dependence of the injection aperture vs field strength.

* Research on controlled thermonuclear reactions is a joint program of General Atomic and the Texas Atomic Energy Research Foundation.
† John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic Division of General Dynamics Corporation, San Diego, California.

F8. Optical Observations in an Isolated Cusp Magnetic Field.* H. G. VOORHIES, R. WENZEL, AND F. R. SCOTT, *General Atomic.*†—Observation of the shape of D_β emission lines from the central plane of the isolated cusp field reported in the previous paper will be discussed. At a peak field strength on axis of 2580 gauss, a complete diamagnetic signal was observed in the injection throat. With this field, the time-dependent shape of the D_β line indicated a peak ion density of 7.6×10^{15} ions/cm³ with a mean life of 22 μsec. Data will be presented on the time-dependent behavior of emission lines of helium and hydrogen as well as deuterium for the various pertinent cusp field strengths. Comparisons of the observed densities, field strengths, and "confinement" times with expectations will be made.

* Research on controlled thermonuclear reactions is a joint program of General Atomic and the Texas Atomic Energy Research Foundation.
† John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic Division of General Dynamics Corporation, San Diego, California.

F9. Asymmetric Collapse Accelerators for Cusps with Internal Injection.* RALPH W. WANIEK, *Advanced Kinetics, Inc.*, HEINZ FISCHER, *U. S. Air Force Cambridge Research Center*, AND K. PARK, *Advanced Kinetics, Inc.*—Experiments have been conducted to gain information on the mechanism of collapse[1] in asymmetric strong-gradient geometries. Single-turn conductors featuring conical and other contoured profiles were coupled to a low inductance storage bank and switching arrangement and were operated up to the limit of the magnetic yield point.[2] Appropriate detection equipment was used to investigate sheath formation, the collapse process, and the details of plasma ejection. Velocities of the luminous front up to 10^8 cm/sec have been obtained in hydrogen at around 50-μ pressure. Kerr-cell pictures at the geometry exit indicate the existence of instabilities generated during the process of compression and acceleration. The use of such shaped magnetic ejectors compounded into a double unit forming a cusp[3] will be described.

* Research supported by the Electronics Research Directorate of the U. S. Air Force Cambridge Research Center.
[1] S. A. Colgate and R. E. Wright, *Proceedings of the Conference on the Peaceful Uses of Atomic Energy*, (Geneva, 1958), U. S. paper 368.
[2] H. P. Furth, M. A. Levine, and R. W. Waniek, Rev. Sci. Instr. 28, 949 (1957).
[3] J. Berkowitz *et al.*, footnote 1, U. S. paper 1538.

F10. Interaction of Plasma Beams in Transverse Magnetic Fields.* HAROLD P. EUBANK, *Project Matterhorn, Princeton University.*—Results are presented from an experimental study of two and three interacting plasma streams obtained from Livermore-type[1] wafer sources, with front velocities of the order of 10^7 cm/sec perpendicular to applied magnetic fields of 0.5 to 20 kgauss. Stream densities are of the order of 10^{14} particles per cm³. Strong repulsive interactions of the fronts are evidenced by high-speed photography. Significant fractions of the injected streams can be trapped in magnetic mirror geometries by what appears to be "peel-off" of the outside sheaths. The decay, as evidenced by probes, may be fitted to a t^{-x} relationship, where x decreases from 2.1 at 1.6 kgauss to 1.4 at 13.2 kgauss.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] F. H. Coensgen, W. F. Cummings, and A. E. Sherman, Phys. Fluids 2, 350 (1959).

F11. Experimental Investigation of the Trochotron Instability.* PHILIP THOMPSON AND E. G. HARRIS, *The University of Tennessee.*—An instability which occurs in a trochoidal electron beam in crossed electric and magnetic fields was discovered and studied by Alfvén *et al.*[1] A possible theoretical interpretation has been given by Harris.[2] The theoretical instability criterion is $\omega_p^2>\omega_c^2$ where ω_p and ω_c are the plasma and cyclotron frequencies, respectively. We have attempted to verify experimentally this criterion. In our experiment the beam moves in a circular path between coaxial electrodes. Magnetic mirrors are used to prevent the escape of electrons along the field lines. Preliminary results show that the instability threshold has the predicted dependence on magnetic field, but the beam becomes unstable at a much lower density than is predicted.

* Supported by the U. S. Atomic Energy Commission.
[1] H. Alfven, L. Lindberg, K. G. Malmfors, T. Wallmark, and E. Astrom Kgl. Tek. Högskol. Handl., No. 22 (1948).
[2] E. G. Harris, Phys. Rev. Letters 2, 34 (1959).

Invited Papers

G1. Velocity Space Instabilities in the Mirror Machine. RICHARD F. POST, *Lawrence Radiation Laboratory.*

G2. Energy Distribution of Protons in DCX. C. F. BARNETT, *Oak Ridge National Laboratory.*

G3. Magnetic Acceleration of Plasma. RALPH H. LOVBERG, *Los Alamos Scientific Laboratory.*

Waves in Plasma

H1. Propagation of Long Wavelength Waves in a Plasma. RICHARD LIBOFF, *Institute of Mathematical Sciences, New York University.*—Small displacements from equilibrium of a charge neutral two-component plasma embedded in a uniform magnetic field are considered. The equations of motion are two Boltzmann-like equations with modified collision terms and Maxwell's equations. The collision terms contain electron-electron and ion-ion collision frequencies, together with two other weighted total cross sections which evolve as being related to the electrical conductivity and thermal diffusion coefficients. These equations thus far have been examined in the limit of small wave number. Two fundamental classes of roots evolve in this limit, viz., $\omega=0$; $\omega\neq0$. The former class yields MHD, while the latter might be described as being indicative of cooperative phenomena, and yields to lowest order

$$2i\omega=[\nu_1'+i(\Omega+\bar{\Omega})]\pm\{\nu_1'[\nu_1'+2i(\Omega+\bar{\Omega})]-[4\omega_0^2+(\Omega-\bar{\Omega})^2]\}^{\frac{1}{2}}$$

for flow normal to the magnetic field. Ion quantities carry a

bar; electron quantities are bare. Primed frequencies include the reduced mass: $m\bar{m}/m+\bar{m}$. ν_1 is related to the electrical conductivity; Ω is the Larmor frequency, and ω_0 is the plasma frequency. For flow parallel to the magnetic field ω is given by the above with $\Omega=\bar{\Omega}=0$. Propagation satisfying $k\cdot B=0$ was considered separately. The classical singularities about integral multiples of the Larmor frequency viz., $\omega=N\Omega$, now occur about $\omega_N=i\nu+\Omega N$, where ν is a self-collision frequency. About these frequencies we find that, for small wave number k, (1) ω behaves as $k^{2(N-1)}$, (2) the purely oscillatory part of ω depends on ω_0, ν_1, and Ω, and (3) about every ω_N there are two eigenfrequencies.

H2. Quasi-Hugoniot Relationships for Low Mach Number Hydromagnetic Compressional Disturbances. H. HURWITZ, JR., AND P. L. AUER, *General Electric Research Laboratory.*—It was reported[1] previously that, although compressional hydromagnetic disturbances in an idealized plasma do not develop conventional shock structures for Mach number less than two, the plasma-vacuum interface velocity observed in a numerical integration of the nonlinear equations of motion is almost identical to that which would be calculated by elementary shock theory with a specific heat ratio of two. An explanation of this observation has been sought on the basis of a two-region model of the disturbed portion of the plasma. In the first region the plasma has basically its original density, but it is traversed by a uniform train of almost independent hydromagnetic pulses. In the second region the plasma is compressed by the ratio of vacuum magnetic field to original magnetic field and is moving uniformly with the plasma-vacuum interface velocity. By employing conservation relations for mass, momentum, and energy, together with the added condition that the pulses accelerate until their spacing somewhat exceeds their width, it is possible to explain the interface velocity, the pulse velocity, and the pulse spacing observed in the numerical integration.

[1] P. L. Auer *et al.*, Bull. Am. Phys. Soc. Ser. II, 5, 353 (1960).

H3. Large Amplitude Magnetic Compression of a Collision-Free Plasma. R. W. KILB, P. L. AUER, AND H. HURWITZ, JR., *General Electric Research Laboratory.*—Previously reported calculations of strong magnetic compression disturbances with orbit crossing were based upon a model in which the positive and negative particles remain together in an orbit crossing event.[1] Similar calculations have now been performed on the basis of an alternate model in which only the ion orbits cross and the electrons retain their original spatial ordering. It can be argued that this model describes the situation in which the ion to electron mass ratio is large. As in the earlier calculations, the ion orbit crossing gives rise to an effective increase in entropy which makes possible a collisionless hydromagnetic shock. In contrast to the earlier calculations, the characteristic length becomes the ion cyclotron radius rather than the electron cyclotron radius when the Mach number exceeds two. The peak electron energy is small compared to the ion energy which suggests that there is little electron heating when the Mach number is more than two but finite. The gross features of the numerical results are insensitive to electron mass, but it appears essential to retain a nonzero electron mass to prevent the solution from becoming singular.

[1] P. L. Auer *et al.*, Bull. Am. Phys. Soc. Ser. II, 5, 353 (1960).

H4. On Rapidly Filling a Stellarator with Plasma.* D. DIMOCK AND J. DAWSON, *Project Matterhorn, Princeton University.*—If the β (ratio of plasma pressure to magnetic pressure) in a stellarator is increased rapidly, the secondary currents necessary to neutralize the particle drifts in the curved magnetic fields must also increase. The inductive potential necessary to increase these currents results in an electric field appearing across the plasma, which causes an $\mathbf{E}\times\mathbf{B}$ drift of the plasma. The magnitude of the resulting displacement is sensitive only to find the final β, and L the length of the current path parallel to the magnetic field, and is of the order of βL for several useful configurations. This results in a critical limitation on any stellarator which is to achieve a hot plasma in times less than that required for an ion to traverse the distance L at thermal velocities. Detailed theoretical results will be presented for several geometries. Possible stellarator configurations minimizing the effect will be discussed.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

H5. Theory of "rf Confinement" Experiments at Low Frequencies.* H. S. BUTLER, *Lockheed Missiles and Space Division,* AND G. S. KINO, *Microwave Laboratory, Stanford University.*—It has been observed experimentally that the application of a radio-frequency field (1 kc/sec–10 Mc/sec) to certain electrode configurations around the outside of a plasma discharge tube leads to a constriction of the light-emitting portion of the plasma away from the walls of the glass tube. The signal from a square wave generator will produce analogous results. This constriction, erroneously labeled rf confinement, is actually a high-voltage dc sheath formed by an interaction of the plasma with the rf field. A description will be given of the dependence of the interaction on the plasma density, the wall potential, and the frequency and amplitude of the rf signal. In addition, a theory will be presented which not only predicts the gross features of the interaction but also gives quantitative agreement with the experiments.

* Supported in part by Air Force Office of Scientific Research, Air Research and Development Command.

H6. Comparison of the Equilibrium Properties of Resonant Cavity Modes for Containment of Dense Plasma Cores.* ALBERT J. HATCH, *Argonne National Laboratory.*—An approximate analytical method has been developed for comparing the equilibrium properties of resonant cavity modes for containment of small sharply bounded dense plasma cores ($\omega_p^2>\omega^2$). The quantity $\mathcal{T}=\frac{1}{2}\mu_0H^2-\epsilon_0E^2$ is calculated and plotted as a function of position within the cavity. Yankov[1] has pointed out that $\mathcal{T}$ is proportional to the field energy displaced by a small perfectly conducting test sphere and that $-\nabla\mathcal{T}$ represents the time average force on the sphere. Thus the plots provide a visualization of the potential surfaces generated in the cavity by the test sphere and of the potential wells within which stable containment may be expected to occur. When the sphere is situated in the vicinity of a field node ($H=E=0$) which is at the bottom of a potential well ($\frac{1}{2}\mu_0H^2>\epsilon_0E^2$), then the field provides a zone within which the sphere is in stable equilibrium against perturbations in size and position. The method has been applied to the TE and TM modes of a spherical cavity. The only modes found to possess the necessary equilibrium properties are the TE_{np0} modes with $n=2, 3, 4, \cdots$ and $p=1, 2, 3, \cdots$. These are the magnetic quadrupole and higher order magnetic multipole modes which are the alternating field counterparts of the cusp and the picket fence type of static magnetic fields.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] V. V. Yankov, Soviet Phys.—JETP 10, 158 (1960).

H7. Effect of Charge Separation on Large Amplitude Pulses in a Cold Plasma.* EDWARD C. TAYLOR AND FRED A. WOLF, *University of California, Los Angeles.*—Pulses propagating perpendicular to a unidirectional magnetic field in a cold neutral plasma were obtained by Adlam and Allen.[1] To investigate the effect of charge separation, we use a technique suggested by Baños and Vernon.[2] We expand the complete system of equations (without the imposition of charge

neutrality) in a small parameter κ, which is proportional to $(v_A/c)^2$, where v_A is the Alfvén speed and c is the speed of light. We set the charge number densities of ions and electrons equal to each other to zero order in κ. The equations governing the zero-order terms are those used by the previous authors for a neutral plasma. We solve the first-order equations, obtaining analytic expressions for the solutions. The expansion remains valid up to and including the upper limit of the Alfvén Mach number, $\alpha=2$. We present profiles of the zero-order solutions and the first-order corrections for $\alpha=\sqrt{2}$ and $\alpha=2$. The corrections preserve the symmetry of the neutral-plasma solutions.

* Supported by the U. S. Atomic Energy Commission through the Lawrence Radiation Laboratory, Berkeley and Livermore.
[1] J. H. Adlam and J. E. Allen, Phil. Mag. 3, 448 (1958).
[2] A. Baños, Jr., and R. Vernon, Nuovo cimento 15, 269 (1960).

H8. Effect of Charge Separation on Large-Amplitude Pulses in a Plasma with Isotropic Pressure.* FRED A. WOLF AND EDWARD C. TAYLOR, *University of California, Los Angeles.*—Baños and Vernon[1] have obtained, under the assumption of no charge separation and finite isotropic pressure, one-dimensional, time-independent, large-amplitude waves and pulses in a collisionless plasma in a reference frame moving at constant speed perpendicular to the magnetic field. The effect of charge separation is obtained as presented in the preceding abstract. The first-order expressions exhibit the same symmetry properties as the zero temperature corrections. However, the fractional charge separation $(N-n)/n$, where N and n are the ion and electron number densities, respectively, approaches infinity in the neighborhood of the peak of the pulse is propagating at the upper limit of Alfvén Mach number $\alpha=\alpha_+<2$. Consequently, the expansion breaks down and the zero-order solutions are incorrect in this vicinity for α near α_+. Profiles of the zero- and first-order solutions are presented for one value of $\alpha<\alpha_+$. Exact solutions of the complete system of equations without imposing charge neutrality for the case $\alpha=\alpha_+$ will be examined in the near future.

* Supported by the U. S. Atomic Energy Commission through the Lawrence Radiation Laboratory, Berkeley and Livermore.
[1] A. Baños, Jr., and R. Vernon, Nuovo cimento 15, 269 (1960).

H9. Ion Structure of Plasma Shock Waves in a Transverse Magnetic Field.* GERALD G. COMISAR, *University of California, Los Angeles.*—The solution of the Boltzmann-Fokker-Planck equation for the distribution of ions in a strong shock wave moving through an unbounded hot plasma has been obtained. The plasma shock front is assumed to travel at constant speed with its normal perpendicular to a stationary magnetic field. The use of Rosen's method of restricted variations,[1] together with Mott-Smith's bimodal trial function,[2] leads to a nonlinear ordinary differential equation for the ion number density n as a function of the normalized distance ξ along the wave normal. For strong shock waves (magnetic Mach number $M_B\gg1$) the inverse relation $\xi=\xi(n)$ has been obtained. The features of the shock profiles resulting from this solution will be discussed for the case of a high-density laboratory plasma ($n_0=10^{16}$ ions/cm^3, $T=10^{6}$°K).

* This work was supported by the U. S. Atomic Energy Commission through the Lawrence Radiation Laboratory, Berkeley and Livermore.
[1] P. Rosen, J. Chem. Phys. 22, 1045 (1954).
[2] H. M. Mott-Smith, Phys. Rev. 82, 885 (1951).

H10. Conductivity of Plasmas to High-Frequency Electric Fields.* TOYOKI KOGA, *Engineering Center, University of Southern California.*—By assuming a mode of distribution, Margenau[1] solved the Boltzmann equation for electrons, under the assumptions that (a) the collision frequency of electrons is low as compared with the frequency of electric field ω, and (b) the amplitude of electric field E_0 is small. The first approximation of current is linear with respect to E_0. But higher approximations seem to involve terms of higher powers of E_0.[2] In the present paper, the same Boltzmann equation is solved under assumption (a), regardless of (b). The scheme of solving the equation is similar to what was presented by the author at the 1959 meeting of Division of Plasma Physics. We obtain current j expanded in a power series of (collision frequency)/ω. The first approximation is the same as that of Margenau. However, the relation between E_0 and j is linear, regardless of the order of approximation, and is different from the result of Margenau's theory. The reason of the discrepancy will be given.

* Supported by the Office of Scientific Research, U. S. Air Force.
[1] H. Margenau *et al.*, Phys. Rev. 69, 508 (1946); 112, 1437 (1958).
[2] M. Epstein, Phys. Fluids 3, 1016 (1960).

H11. Nature of Electromagnetic Waves in Nonhomogeneous, Anisotropic Plasmas. M. P. BACHYNSKI, *RCA Victor Company Ltd., Montreal.*—The general equations for time harmonic, electromagnetic fields in unbounded nonhomogeneous, anisotropic media are set down using the notion of a tensor dielectric coefficient whose elements may be functions of position in the medium. The general equations can be reduced readily to a vector differential equation or equivalently to a set of component scalar equations in terms of the magnetic vector. The more specialized cases of electromagnetic waves in isotropic inhomogeneous, anisotropic homogeneous, and isotropic media are contained in the general relations. From these relations can be deduced the nature of initially plane waves propagating in anisotropic, inhomogeneous media. In addition, the solution of the electromagnetic equations can in some cases be reduced to one of solving a differential equation for the refractive index.

H12. Ionic Sound Waves in Thermionic Plasma Diodes. EDWARD KUHN, *Republic Aviation Corporation.*—Based on the theory[1] that trapped positive ions in a negative space charge well generate ionic sound waves of the Tonks-Langmuir[2] type, it is shown that the condition $eV_w/kT_e\ll1$ need not be invoked to derive the dispersion relation

$$\omega^2=\frac{\omega_i^2}{1+(\lambda/\lambda_D)^2}.$$

This relation has been used to explain observed[3] oscillations in thermionic plasma diodes. Application of these ionic sound wave signals ($\sim10^5$ cps) as a diagnostic for the determination of average ion density in the well, length of the well, and position of space charge maximum potential will be discussed.

[1] J. F. Waymouth, Sylvania Technologist 13, 2 (1960).
[2] L. Tonks and I. Langmuir, Phys. Rev. 33, 195 (1929).
[3] M. Gottlieb and R. J. Zollweg, Bull. Am. Phys. Soc. Ser. II, 5, 383 (1960).

Stellarator Experiments

I1. Loss of Charged Particles during Ionization in Stellarator Discharges.* W. STODIEK,† R. A. ELLIS, JR., AND J. G. GORMAN,‡ *Project Matterhorn, Princeton University.*—It has been shown that there is a rapid loss of charged particles from stellarator discharges during the ionization phase which gives confinement times proportional to the magnetic confining field. In the present paper, the effect of the electron temperature on the particle loss rate is presented.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† On leave from Max-Planck Institut fur Physik und Astrophysik, Munich.
‡ On loan from Westinghouse Electric Corporation.

I2. Rapid Loss of Particles from the Plasma of the Étude Stellarator.* ROLF M. SINCLAIR, *Project Matterhorn, Princeton University.*—The Étude stellarator is characterized by a low confining magnetic field B and a low ohmic heating voltage; the discharges exhibit low ionization rates and relatively low plasma densities. The loss rate from the plasma of charged particles ("pumpout") can be deduced from the observed density by assuming that the loss starts at the beginning of the discharge and persists during the time (typically 250 to 1500 μsec) of ionization and ohmic heating.[1] The mean charged particle confinement time τ so found is an average over the entire discharge. For H_2 discharges at $B=6.74$ kgauss, $\tau=8.2\pm0.6$ μsec over a wide range of experimental variables. The ratio of τ at this B to that at 3.85 kgauss is 1.77 ± 0.09. These results are consistent with the results from the B-3 stellarator at 40 kgauss,[2] assuming τ varies as B and as (plasma radius).[2]

*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] R. A. Ellis, Jr., J. G. Gorman, and W. Stodiek, Bull. Am. Phys. Soc. Ser. II, 5, 341 (1960).

[2] W. Stodiek (private communication).

I3. Afterglow Spectrum of Neutral Helium in the B-1 Stellarator.* E. HINNOV AND J. G. HIRSCHBERG, *Project Matterhorn, Princeton University.*—Emission of light has been observed in the B-1 stellarator discharge after crowbarring the accelerating field. This afterglow is especially pronounced in helium at relatively high pressure (1–5 μ) and high confining fields. The general characteristics of the light emission are: a sudden drop from the discharge pulse value at the moment of crowbar; a gap of practically zero emission, with duration depending on pressure; a fast rise in intensity to a sharp maximum; and, in case of neutral helium lines, a relatively slow decay, which generally parallels the decrease in electron density. The intensity and time behavior of the neutral helium spectrum has been studied under different excitation conditions, pressures, and confining fields. Under some conditions, recombination accounts for substantially all the disappearing electrons. The time behavior of the light is not affected by the conditions of the discharge, except for a weak dependence on pressure. The decay is exponential, with time constants 0.5–1.0 msec. The exact mechanism of recombination has not yet been determined. It is certainly too fast for two-body radiative recombination, and it does not appear to depend on impurities. No series cutoff has been observed up to $n=13(2^3P-n^3D$ series). The triplet to singlet intensities are approximately in the ratio 3:1.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

I4. Afterglow Spectrum of Helium Ions and Impurities in the B-1 Stellarator.* J. G. HIRSCHBERG AND E. HINNOV, *Project Matterhorn, Princeton University.*—In the afterglow described in the preceding abstract, the helium and impurity ion spectral lines behave quite differently from neutral helium. By using radio-frequency excitation, no light due to the helium ion is seen, but, by adding impurities, C II, A I, A II, and hydrogen are visible. Without exception, the decay times of the ions are much shorter than the neutral atomic lines, being about 50 μsec as opposed to the order 1 msec for neutrals. Addition of small amounts of methane and hydrogen changes the afterglow only slightly, while argon is more effective in reducing the intensity of helium afterglow. The impurity spectra take on the appearance of the helium afterglow, the ions closely resembling the helium ion light and the neutrals the helium neutral light. The behavior of these spectra was studied for pressures varying from 0.6 to 4 μ and magnetic fields varying from 5 to 23 kgauss. The afterglow intensity generally increases with increased pressure and increased magnetic field. In view of the similarity of the afterglow behavior with different mixtures, it appears unlikely that a particular process involving an excited intermediate molecular ion is responsible for the afterglow, some direct recombination process seeming more likely.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

I5. Diffusion and Recombination in the Afterglow of Stellarator Discharges.* A. F. KUCKES AND R. W. MOTLEY, *Project Matterhorn, Princeton University.*—A study has been made of the confinement properties of the B-1 stellarator during the afterglow of ohmic heating discharges in helium. The electron density was measured over a range extending from 5×10^{13} to 2×10^{11} electrons/cm^3 by observing the phase shift of 4.3- and 8.6-mm microwaves. After an initial rapid fall, the electron density loss is exponential with time. The initial plasma loss rate is found to vary roughly as $1/B$ and is ascribed to diffusion. The later exponential decay is independent of magnetic field in the range from 29 to 3.5 kgauss and of the plasma diameter. This time constant depends upon neutral pressure roughly as $P^{-\frac{1}{2}}$ in the pressure range from 0.25 to 40 μ. At 1.2 μ it is 0.8 msec which is about 10% of the classical diffusion time at 3.5 kgauss. The intensity of visible light emitted from the discharge is proportional to the electron density loss rate over the entire magnetic field range during the slow decay of the plasma. These data suggest that recombination is the dominant mechanism for plasma loss in the late afterglow.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

I6. Conductivity Measurements in the Afterglow of Helium Discharges in the Stellarator.* R. W. MOTLEY AND A. F. KUCKES, *Project Matterhorn, Princeton University.*—Electron temperatures have been inferred from measurements of plasma conductivity in the afterglow of helium discharges in the B-1 stellarator. The conductivity is calculated from the magnitude of the current induced in the plasma by an alternating electric field at frequencies between 10 and 60 kc. The electron temperature is found to fall from about 5 ev immediately after excitation to about 0.5 v in a time comparable to the expected electron-ion-neutral relaxation time. However, when recombination becomes dominant, the electron temperature falloff proceeds at only a small fraction (1% to 10%) of the calculated rate. The hypothesis that an energy source in the plasma is responsible for the slow falloff of electron temperature was tested by measuring the power required to maintain the electron temperature. The results show that energy is extracted from the plasma at a rate consistent with a He^+-He charge exchange cross section of 3×10^{-15} cm^2. A likely process for feeding energy into the plasma is that of superelastic collisions of electrons with metastable atoms formed by the recombination process. The cross section for this process indicated by the measurements is 1.5×10^{-16} cm^2 (within a factor of two) in the range of electron energies between 0.1 and 0.5 ev.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

I7. Particle Surfaces for High-Energy Electrons in the B-3 Stellarator.* E. B. MESERVEY AND L. P. GOLDBERG, *Project Matterhorn, Princeton University.*—The position at which runaway electrons strike the edge of a limiter in the B-3 stellarator has been measured as a function of confining field, accelerating field, and plasma current. Qualitatively the results agree with the predictions of a simple single particle model of particle surfaces for high-energy electrons. The surfaces are displaced toward the inside of the stellarator loop for plasma current parallel to confining field and toward the outside for plasma current antiparallel. Measured x-ray start times and rough energy measurements are consistent with the single particle model. X-ray bursts are also present which appear to be correlated with plasma current instabilities, as was observed by Kranz, Bernstein *et al.* The relation between the

single particle model for runaway electrons and the hydromagnetic model for the main part of the plasma will be discussed.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

I8. Improvement of Plasma Purity in a Stellarator Discharge by the Use of Ultra-Pure Gas.* E. G. APGAR AND J. G. GORMAN,† *Project Matterhorn, Princeton University.*—Gas impurities and base pressure constituents were monitored with a mass spectrometer mounted on a baked oil-pumped stellarator subjected to helium-discharge-cleaning after being open to the atmosphere. The changes in impurity concentration measured between discharges and the cumulative effects of repeated discharges pointed to the carbon monoxide (one part in 10^4) impurity in the hydrogen as a controlling factor in the discharge characteristics. Reduction of the impurity to one in 10^8 and additional discharge cleaning resulted in about a sixfold decrease in the carbon content of the plasma at peak density as measured by optical spectroscopy methods. An interpretation of the disproportionate effects of a small impurity concentration is given in terms of impurity adsorption on the discharge tube wall. However, these data suggest another source of impurity has become the controlling factor at the improved impurity level.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† On loan from Westinghouse Electric Corporation.

I9. Production of a Quiescent Plasma through the Decay of a Radioactive Gas.* W. BERNSTEIN,† G. MARTIN, AND M. ROTHMAN, *Project Matterhorn, Princeton University.*—The production of a quiescent plasma in a stellarator geometry is of interest in studying the confinement properties of this device. It appears feasible to produce such a plasma in this geometry with a dc magnetic field through the decay of a radioactive gas. It is proposed to use 114-min Kr^{83M}, which decays to stable Kr^{83} by the emission of two highly internally converted γ rays of 32 and 9 kev as the source. In a small stellarator, such as A-2, 1 curie of Kr^{83M}, assuming a ratio of $Kr^{83}/Kr^{83M}=8$, corresponds to a pressure of 10^{-8} mm Hg. Calculations will be presented for the temporal behavior of the electron density for various values of production rate, recombination coefficient, and diffusion time. Because of the low operating pressure, it is possible that radiative recombination will be the dominant recombination process. If classical confinement theory is valid, equilibrium electron densities of about 5×10^{10}/cc should be obtained in 5 sec. The problems involved in the production of curie quantities of Kr^{83M} of sufficient purity through $Se^{83}(n)Se^{83}-Br^{83}-Kr^{83M}$ will be discussed.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† Now at Hughes Research Laboratories, Malibu, California.

Mirrors, Orbits, Miscellaneous

J1. Ambipolar Potentials in a Mirror Machine.* R. F. POST, *Lawrence Radiation Laboratory.*—A plasma composed of energetic ions and electrons of lower mean energy confined by mirrors should develop a positive plasma potential. Since electrons are scattered into the loss cone more rapidly than ions, a plasma potential will develop sufficient to equalize these rates. The equilibrium ambipolar potential distribution in a mirror machine has been calculated under the following assumptions: the electron distribution is Maxwellian (except at energies greater than the plasma potential); the ion energy distribution fits the "normal mode" solution to the mirror loss equations[1]; the particles obey the adiabatic invariants which determine confinement. The calculations show the following general results: For plasma potentials which are substantially greater than the electron mean energy, the gradient of plasma potential along the magnetic lines within the plasma is small and is nearly independent of the value of the potential. Thus most of the potential variation occurs near the mirrors. For a plasma potential $4\ kT_e$ and mirror ratio 3.3, 80% of the particles feel potentials less than kT_e; for $R=10$, 90%. This suggests that the enhancement of mirror losses by ambipolar effects may be smaller than previously estimated.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] A. Garren, R. J. Riddell, L. Smith, G. Bing, L. R. Henrich, T. G. Northrop, and J. E. Roberts, *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy* (Geneva, 1958), Vol. 31, p. 65.

J2. Effect of Plasma Potential on DCX Steady State. T. K. FOWLER, *Oak Ridge National Laboratory.**The energies of ions and electrons in DCX at steady state after "burnout" have been calculated, taking into account the plasma potential. Because electrons are scattered more readily than ions, the plasma charges positively to restrict electron escape. It is shown that the potential reaches a value $\sim\bar{E}_-/e$, where $\bar{E}_-$ is the average electron energy weighted by their leak rate. Thus, an appreciable fraction of the energy transfer to and from the electrons is via reversible interaction with the plasma potential, with the consequences that the energy drain to cold electrons is considerably less than one would estimate, neglecting potential effects.

* Operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

J3. Critical Parameters for Burnout in a Device Fed by Energetic Ions. R. J. MACKIN, JR., *Oak Ridge National Laboratory.**—The general steady-state theory of plasma accumulation (without energy losses) in a device fed by the injection and trapping of energetic ions has been given by Simon[1] for the case of initial trapping by interactions in background gas (e.g., OGRA). Such a device is usually characterized by a critical input current or critical plasma density (a function of input current) above which plasma density builds up to a value limited by Coulomb-scattering losses. For a regime of operation of current interest at ORNL (600-kev hydrogen molecular ion injection and dissociation, highly efficient ion-pumping action of the trapped plasma), extremely simple approximate formulas have been derived which describe with a fair degree of accuracy the critical current or density for plasma build-up. Simon's application of the general analysis to initial trapping by a Luce carbon arc has been extended to give a detailed picture of the plasma density variation as the arc density is varied. Two new points emerge: (1) the critical current for plasma build-up with arc is less than previously estimated by nearly an order of magnitude if the arc is turned off slowly or if an arc of lower density is used; and (2) the critical arc density, below which plasma build-up occurs after the arc is removed, is sufficiently low that energy losses to fixed-temperature arc electrons are not significant. Application to other arc types will be described.

* Operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.
[1] A. Simon, "Critical current for burnout in an OGRA-type device," ORNL-2831 (October, 1959); J. Nuclear Energy, Part C (to be published).

J4. Gas Density Variation during Plasma Build-Up by Neutral Atom Injection.* A. H. FUTCH, C. C. DAMM, W. HECKROTTE, J. KILLEEN, AND L. MISH, *Lawrence Radiation Laboratory, Livermore.*—We previously have described[1] the spatially dependent equations with numerical solutions for plasma formation by energetic atom injection into a magnetic mirror geometry. These considerations have been extended to include the possibility of gas density variation during the plasma build-up. A two-region model for the spatial variation of gas density is employed, the density in the plasma core being allowed to differ from the density elsewhere. Terms are included which account for scattered beam, bombardment of the walls by fast atoms lost from the plasma by charge-exchange, plasma pumping, and gas "burnout" in the plasma core. Numerical solutions have been obtained with parameters chosen to approximate the conditions of a neutral injection experiment at this laboratory. With this selected set of conditions, gas "burnout" and plasma pumping enhance the plasma growth rate and the final plasma density slightly. The gas influx due to wall bombardment by fast atoms was found to result in serious damping of the plasma growth if the number of molecules ejected from the walls per incident atom becomes too large.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] A. H. Futch, C. C. Damm, W. Heckrotte, and J. Killeen, Bull. Am. Phys. Soc. Ser. II, 5, 233 (1960).

J5. Time Dependence of Ion and Electron Temperatures in Scylla.* W. B. RIESENFELD, R. C. MJOLNESS, E. J. STOVALL, AND J. N. GINOCCHIO, *Los Alamos Scientific Laboratory.*—A calculation has been performed to test a simple model of Scylla operation subsequent to the initial ionization and implosion phase. This model describes the temperature development of ions and electrons as a consequence of an adiabatic compression exerted by the applied magnetic field, with simultaneous relaxation of the ion and electron temperatures as given in terms of Spitzer's energy exchange time. Particle and radiation losses are ignored. Analytic solutions of the differential equations describing the model have been obtained. These solutions are normalized to the experimental densities and temperatures at the time of peak magnetic field and serve to display the effect of varying parameters of interest, i.e., the relaxation time scale and equation of state parameter. Curves of ion and electron temperatures as functions of time are plotted for three-dimensional compressions with relaxation time scale as parameter. Comparison with experimental curves shows that the measured ion and electron temperatures at peak compression are consistent with the model only for ion electron relaxation times greater than three times the Spitzer values. Detailed calculations[1] using the Fokker-Planck equation bear out that such an increase in relaxation time is to be expected for distributions in which the ion temperature is much greater than the electron temperature.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] J. Killeen and W. Heckrotte, Bull. Am. Phys. Soc. Ser. II, 5, 372 (1960).

J6. A Qualitative Model of P-4, a Steady-State Plasma Source.* L. S. HALL, A. L. GARDNER, R. L. KELLY,† AND N. L. OLESON,‡ *Lawrence Radiation Laboratory.*—A qualitative analysis is presented describing the physics of the operation of P-4, a steady-state source of a highly (>95%) ionized helium plasma whose experimentally determined characteristics were previously reported[1–3] (e.g., density $\sim 2\times 10^{13}/\text{cm}^3$, ion temperature ~8 ev). Certain features of operation are discussed which it is felt lead to some of its desirable characteristics (e.g., relatively high ion temperature, quiescence), especially as these characteristics refer to the plasma outside the region of the discharge proper. A model qualitatively describing the discharge and plasma column regions is presented.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† Present address: U. S. Naval Postgraduate School, Monterey, California. Work performed while a consultant to LRL from Stanford Research Institute, Menlo Park, California.
‡ U. S. Naval Postgraduate School, Monterey, California.
[1] A. L. Gardner, L. S. Hall, and D. E. Edwards, Bull. Am. Phys. Soc. Ser. II, 5, 313 (1960).
[2] N. L. Oleson and D. M. Gall, footnote 1.
[3] W. L. Barr and R. L. Kelly, footnote 1.

J7. Charged Particle Motion in a Rotating Magnetic Field.* ERNEST P. GRAY, *Applied Physics Laboratory, Johns Hopkins University.*—The equations of motion of a charged particle in a rotating, uniform magnetic field of infinite extent, with the axis of rotation perpendicular to the field, have been solved analytically. It is found that, for rotation frequencies ν less than the cyclotron frequency ν_c, the particle moves away from the axis of rotation in the manner of an exponential spiral, gaining energy from the field on the way. For frequencies $\nu > \nu_c$, the particle remains confined within a finite region, with its energy a periodic function of time. The effect of charge separation in a dilute plasma placed in such a rotating field, and some of the practical difficulties of utilizing such a scheme for plasma confinement, will be discussed.

* This work supported by the Bureau of Naval Weapons, Department of the Navy.

J8. Motion of a Charged Particle in an Axisymmetric Cusped Field near the Zero Field Point.* R. VAN NORTON, *Institute of Mathematical Sciences, New York University.*—The motion of a charged particle in an axisymmetric cusped field near the zero field point was calculated for a variety of initial conditions. The magnetic field is taken to be the asymptotic field which arises from current loops removed to infinity. Calculation of the change in a particle's turning point between two consecutive reflections at the axial mirror indicates a rather sharp boundary between orbits for which the magnetic moment is a constant of the motion and orbits nearer the axis for which a large change in magnetic moment occurs between reflections. An asymptotic estimate of the radius of this boundary is given. Calculational results which led to this estimate are shown.

* Supported by the U. S. Atomic Energy Commission.

J9. Analog Computer Study of Cusp Confinement.* R. C. ISLER AND E. P. GRAY, *Applied Physics Laboratory, Johns Hopkins University.*—Simulation on an analog computer was used to study the equations of motion of charged particles in an axially symmetric magnetic mono-cusp. For ease of simulation, a vector potential in the azimuth direction (of a cylindrical coordinate system) of magnitude proportional to rz was used to generate the field. Particles injected at either the line or the point cusp along various initial directions were followed for up to 30 Larmor periods (corresponding to 1–2 μsec for protons in 30 kgauss), beyond which the computer error invalidated the results. While many initial conditions lead to rapid escape, some—especially azimuthal injection at the line cusp—apparently lead to containment. These trapped particles are usually confined to the strong-field regions far from the cusp center and behave somewhat like particles trapped in a mirror geometry in that their magnetic moment remains reasonably constant (10–20%). Particles reaching the weak field central region usually escape, and their magnetic moment undergoes large, apparently random fluctuations.

* This work supported by the Bureau of Naval Weapons, Department of the Navy.

J10. Theory of an Electrostatic Probe in a Strong Magnetic Field.* BRUNO BERTATTI, *Project Matterhorn, Princeton Uni-*

versity.—If the magnetic field **B** is so strong as to impair collective transverse drifts, all the charges supplied to the probe come mainly from a long cylinder parallel to **B**, whose section is about one Larmor radius larger than the probe, while a diffusion process, more efficient than ordinary drifts, exchanges continuously particles between inside and the rest of the plasma. We propose a one-dimensional model of this process, leading to an integro-differential Poisson's equation, of which a preliminary study is given. The legitimacy of neglecting second-order drifts also is discussed.

* Work accomplished under the auspices of U. S. Atomic Energy Commission.

J11. Plasma Confinement Pressure as a Conservative Extraneous Body Force. RICHARD L. MOORE,* *R. L. Moore Consultants.*—The irrotational *extra stress* gradient due to the surface force of a cylindrical magnetic bottle with plasma radius r_0 is shown rigorously by means of the classical hydrodynamic continuum theory[1a] to be equivalent to a conservative extraneous body force, $-1_r\pi r H_z(r_0)B_z(r_0)M^{-1}$ (rationalized mks units; M is lineal plasma density). As a consequence all the scaling laws[1b] applicable to an ideal inviscid fluid under conservative extraneous body forces may be applied to plasma motion. The quasi-steady state density distribution is Gaussian in agreement with a recent interpretation of experimental measurements.[2] Interpretation of experiment will be given for flow through constrictions and radial, torsional, and longitudinal vibrations. This same technique may be applied to such diverse phenomena as compressible supersonic flow of a jet from an orifice and the atomic nucleus considered as a drop of *compressible* fluid.

* Sponsored by Northrop Corporation, Norair Division, under contract to ARDC, Rome Air Development Center.
[1] C. Truesdell, (a) J. Math. and Mech. 1, 125–300 (1952) and (b) Mem. Sci. Math. No. 119, Paris, 1952.
[2] R. L. Moore, "A re-examination of the meaning of magnetic probe measurements," Gaseous Electronics Conference, 1960.

J12. Electron Capture Cross Section in a Magnetic Field. WALLACE G. STONE, *Army Rocket and Guided Missile Agency, Redstone Arsenal.*—A classical calculation has been made of the cross section for "remote capture" of electrons by ions in the presence of a magnetic field. The magnitude of the magnetic field controls the boundary conditions of Debye length and mean free path in which the mechanism is significant but does not explicitly affect the average cross sections.

$$\bar{Q}=\frac{2\times10^{17}}{v^4}\text{cm}^2.$$

The number of such "remote captures" that terminate in true radiative capture is less than this cross section by one or two orders of magnitude, but all contribute to diffusion of ions and electrons across magnetic lines.

J13. A Fundamental Error in Thermonuclear Research Continues to be Accepted. JOSEPH SLEPIAN, *Pittsburgh.*—In replying to my Letter[1] on this subject, A. Simon justifies his dropping the $\rho\mathbf{v}\cdot\nabla\mathbf{v}$ term from his equation of motion of a plasma in his 1959 book by referring to L. Spitzer's 1956 book containing a reference to a paper by A. Schlüter.[2] This refers only to an equilibrium between mass weight and magnetic field and so does not include an equilibrium between mass only and a magnetic field, however dilute. Now there have appeared two new books, one by C. Longmire, J. L. Tuck, and W. B. Thompson[3] and the other by William P. Allis,[4] both of which contain a selected list of papers of the Second Geneva Conference. These books contain frequently, too, the error that, for a hot plasma within a simply connected surface maintained at a low temperature, the equation of the plasma has been abbreviated by dropping $\rho\mathbf{v}\cdot\Delta\mathbf{v}$ from grad $p=\langle\mathbf{j}\rangle\times\langle\mathbf{B}\rangle$.

[1] J. Slepian, Phys. Fluids 3, 490 (1960).
[2] A. Schlüter, Z. Naturforsch. 5a, 72 (1950).
[3] C. Longmire, J. L. Tuck, and W. B. Thompson, *Plasma Physics and Thermonuclear Research* (Pergamon Press, New York, 1959), Vol. 1.
[4] W. P. Allis, *Nuclear Fusion* (D. Van Nostrand Company, Inc., Princeton, New Jersey, 1960).

J14. Ball Lightning—a Survey. J. R. MCNALLY, JR., *Oak Ridge National Laboratory.**—Ball lightning is a possible stable plasma configuration and hence may merit some consideration in the field of thermonuclear research.[1] A survey of 15 923 Union Carbide Nuclear Company personnel in Oak Ridge has been made with 498 reports of unusual lightning phenomena which the observers thought may have been related to ball lightning. Some of the results of the survey will be presented.

* Operated by Union Carbide Nuclear Company for the U. S. Atomic Energy Commission.
[1] P. L. Kapitza, Proc. Acad. Sci. U.S.S.R. 101, 245 (1945); V. D. Shafranov, J. Exptl. Theoret. Phys. (U.S.S.R.) 33, 710 (1957) [translation in Soviet Phys.—JETP 6, 545 (1958)].

Pinches and Diagnostics

K1. Time Resolved Plasma Electron Temperatures >100 ev.* T. F. STRATTON, E. M. LITTLE, AND W. E. QUINN, *Los Alamos Scientific Laboratory.*—Previously reported experiments have demonstrated that it is possible to determine the electron temperature of plasmas with $kT_e>100$ ev by an absorption analysis of the bremsstrahlung and recombination continuum.[1] Difficulties arising because of imperfect knowledge of the ionization states can be avoided by selecting absorbers whose principal transmission is at energies well above the ionization thresholds of possible ionic species. When this requirement is satisfied, the experimental measurement of only two points of an absorption curve is sufficient to determine the electron temperature, irrespective of the density and contamination. A soft x-ray absorption analysis system consisting of two collimeters, two (different) absorber foils, and two scintillation detectors has been constructed and calibrated for application to deuterium discharges in the Scylla fast magnetic compression experiment. It has been established that the photomultiplier signals are identical when the foils are identical and that the temperatures obtained from the present analysis are in agreement with the previous work. A time resolved study of the signals from the two detectors shows that the highest electron temperature is reached about 0.5 μsec after the peak of the confining magnetic field (2.5 μsec half-period), in qualitative agreement with the observation that the electrons must be heated by energy partition from the higher temperature deuterons as well as by the adiabatic compression of the magnetic field.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] F. C. Jahoda, E. M. Little, W. E. Quinn, G. A. Sawyer, and T. F. Stratton, Phys. Rev. 119, 843 (1960).

K2. Electron Temperatures with Preionized Scylla.* W. E. QUINN, E. M. LITTLE, AND T. F. STRATTON, *Los Alamos Scientific Laboratory.*—Electron temperature determinations have been obtained for deuterium discharges in Scylla with pinch preionization and parallel, zero, and antiparallel externally applied quasi-static axial magnetic fields (B_θ). For zero and antiparallel B_θ, electron temperatures in excess of 100 ev are obtained during the first half-cycle of the oscillatory compression field; for parallel B_θ, electron temperatures much less than 100 ev are observed. All conditions of B_θ result in tem-

peratures in excess of 100 ev during the second half-cycle, but the values are always lower than the corresponding temperature without pinch preionization and B_θ, presumably because of greater contamination introduced by the pinch. The absence of an appreciable electron temperature on the first half-cycle with parallel B_θ is consistent with the absence of neutron emission. However, with zero B_θ the electron temperature is comparable to that with antiparallel B_θ while the neutron emission is very small relative to the antiparallel case. When the 100-kv, 200-kc capacitor bank is supplemented with a 20-kv, 30-kv power crowbar bank to extend the magnetic field in time, the electron temperature with pinch preionization and antiparallel B_θ is approximately constant for about 2.5 μsec at a value of about 120 ev. The electron temperature decreases earlier than the neutron emission. The data suggest that a complete interpretation must include both radiation losses and particle losses through the magnetic mirrors.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

K3. Fission of Plasma Produced by a Fast Magnetic Compression. ALAN KOLB, *U. S. Naval Research Laboratory* AND NORMAN ROSTOKER,* *General Atomic.*—It has been observed that the plasma formed in a fast B_z compression is initially cylindrical. It subsequently flattens into an elliptic cylinder and then fissions into two filaments which are observed to rotate with an angular velocity $\omega \sim 10^7$ sec^{-1} in the same sense as the deuterium ions. The plasma evidently develops an angular velocity which results in an exchange of stability from the cylindrical to the filamentary configuration. The latter configuration is observed for many rotational periods during which the plasma appears to remain confined, although impurity radiation indicates some plasma reaches the walls during the fission process. A phenomenon that appears quite similar has been observed with rotating jets from shaped charges.[1] Present conjectures about the physical origin of the rotation and fission will be presented.

* Work supported by a joint program on controlled thermonuclear reactions of General Atomic and the Texas Atomic Energy Research Foundation.
[1] R. Schall and G. Thomas, *Actes du 2 me Congrès International de Photographie et Cinématographie Ultra Rapide* (Dunod, 92 Rue Bonaparte, Paris, 1956), p. 261.

K4. Neutron Producing Mechanism in Transverse Pinches. V. JOSEPHSON, M. DAZEY, AND R. WUERKER, *Space Technology Laboratories, Inc.*—Experiments performed on a transverse pinch assembly show that the presence of a longitudinal magnetic field inside of a conducting plasma and in the reverse direction to that of the external pinching field results in the generation of the $m=0$ (sausage) instability mechanism. This instability mechanism can generate high electrical fields which will accelerate deuterons to energies sufficient for neutron production in deuterium plasmas. Subsequent to the blowup of the instability, the plasma field configuration is such that the accelerated deuterons can continue to circulate in stable orbits until lost by neutron-producing collisions or by diffusion out of the ends of the geometry. Experimental data in the form of smear photographs, Kerr cell photographs, and oscilloscope traces of magnetic probe signals are presented, illustrating the time history of this instability mechanism.

K5. Sheath Formation and Azimuthal Inhomogeneities in a Linear Pinch Tube.* C. L. OXLEY AND DONALD J. ALBARES, *General Atomic.*†—Sheath formation in a 16×100-cm alumina linear discharge tube with thin stainless steel electrodes and a uniform original B_z has been studied by conventional probe techniques. At low B_{z0}, sheaths of approximately 1-cm thickness were formed as has been commonly observed. At B_{z0}'s comparable to B_θ at the wall at current maximum, the current held at the wall and diffused in slowly. The condition of highest current density at the tube center from early times, as observed in a smaller tube in this laboratory,[1] was not found in the larger tube even when some of the B_z field imperfections of the small tube were mimicked in an exaggerated way. Current filaments originating at holes in an electrode were observed by azimuthal exploration of B_θ at the tube wall. Their characteristics and some effects of electrode change as observed by Kerr cell photographs will be discussed.

* Research on controlled thermonuclear reactions is a joint program of General Atomic and the Texas Atomic Energy Research Foundation.
† John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic Division of General Dynamics Corporation.
[1] Brower *et al., Proceedings of the Second United Nations Conference on Peaceful Uses of Atomic Energy* (Geneva, 1958), Vol. 32, p. 110.

K6. Rayleigh-Taylor Instability, Observations in the Linear Pinch.* DONALD J. ALBARES AND NICHOLAS A. KRALL, *General Atomic.*†—Under certain conditions the plasma produced in the stabilized linear pinch tube is a hollow cylinder of ionized gas, initially accelerating inwards, compressing a trapped magnetic field B_z. Kerr cell photographs of the inner surface of this cylinder reveal that when B_z is compressed enough so that it overbalances the pinching field, and the acceleration of the plasma becomes directed radially outwards, sharp irregularities appear and grow with time. We associate these growing perturbations with the Rayleigh-Taylor instability,[1] since we have light fluid (B_z) accelerating a heavy fluid (the plasma); we show that the perturbations exhibit approximate exponential growth during their early history, with growth rate[1] appropriate to the Rayleigh-Taylor instability. The tube current was varied from 150 to 250 kamp, B_z from 0.5 to 2.0 kgauss, and the electrode shape was changed. These variations alter most features of the plasma, but the appearance of the growing perturbations on the inner surface when the acceleration becomes outwardly directed persists, as expected, if the interpretation is correct.

* Research on controlled thermonuclear reactions is a joint program of General Atomic and the Texas Atomic Energy Research Foundation.
† John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic Division of General Dynamics Corporation, San Diego, California.
[1] M. Kruskal and M. Schwarzschild, Proc. Roy. Soc. (London) **A223**, 348 (1954).

K7. Pinch Effect Studies with Exploding Wires.* J. KATZENSTEIN AND M. SYDOR, *University of New Mexico.*—The high-current electric discharge through small-diameter conductors has been studied under conditions which should maximize the confinement of the discharge by the self-magnetic field.[1] A condenser bank of 1.75 μf charged to 93 kv is discharged through a one-mil polyethylene filament in high vacuum which has been made conducting by a coating of Aquadag. Streak camera photographs of the discharge indicate confinement times up to 3 μsec or one full current cycle of the discharge. Disruption of the discharge by what appear to be spiral instabilities also is indicated by these photographs. Waveforms of the voltage across the wire are taken with a resistive divider. The frequency response of this divider is inadequate to show voltage variations which would correspond to the fast inductance changes of the pinch. The voltage is observed to fall to only a few percent of the initial potential on the capacitors in about a microsecond, indicating a very rapid transfer of energy. Studies of neutron production with deuteropolyethylene fibers using a silver-foil Geiger counter are in progress and will be reported.

* Work supported under a grant from the National Science Foundation.
[1] J. Katzenstein, *Exploding Wires* (Plenum Press, Inc., 1959), p. 135.

K8. Electron Beam Probing of the Pinch.* S. A. COLGATE, C. W. HARTMAN, AND R. L. SPOERLEIN, *Lawrence Radiation Laboratory.*—A high-energy (100- to 400-kev), low-current

(10- to 100-ma), pulsed (0.1-μsec) electron beam has been passed along the magnetic field lines of a 100- to 200-ka "stabilized pinch" and observed as a luminous spot on a phosphor at the exit electrode of the pinch. During the period of gross stability of the pinch ($\sim$5 μsec), when the beam enters on axis, it also exits on axis. When the beam is injected off axis, it passes through a region where, at first, the field lines are purely axial but gradually become helical as B_θ-field diffuses in. The beam spot then circles about the axis at a rate determined by the resistivity of the plasma. Over the length of the pinch tube (40 cm) the beam is observed to defocus from a 1-mm diam spot to one of 1-cm diam. This degree of defocusing can be predicted on the basis of the observed (with magnetic probes) random or turbulent magnetic field vector; and, in turn, this degree of defocusing could not be predicted from transverse electric fields unless $E \geq 20$ kv/cm. The observed defocusing confirms a previously predicted[1] short containment time for runaway electrons in toroidal stabilized pinches.

* This work was done under the auspices of the U. S. Atomic Energy Commission.

[1] S. A. Colgate, J. P. Ferguson, and H. P. Furth, *Proceedings Second United Nations Conference on Peaceful Uses of Atomic Energy* (Geneva, 1958), Vol. 32, p. 129.

K9. Observations of Pinching Time and Stability of an Electron-Hole Plasma in Indium Antimonide. M. GLICKSMAN AND R. A. POWLUS, *RCA Laboratories.*—The time-dependence of the electrical properties of electron-hole plasmas generated by collision ionization across the forbidden gap in n-type indium antimonide have been observed in pulsed studies at 77°K. The behavior of the current and voltage during the pulses provides evidence confirming the occurrence of a pinching of the plasma current, suggested in explanation[1] of earlier observations of the average dependence of current on the voltage. The time for the pinch to progress to apparently its first minimum in radius decreases from about 0.7 μsec near the threshold current to less than 0.025 μsec at the highest currents, which correspond to an initial current density of 10^4 amp/cm^2. The variation of this pinching time with current is in agreement with theoretical predictions. The pinch is apparently stable for times at least as long as 1.4 μsec in the absence of an applied magnetic field. An applied longitudinal magnetic field causes an increase in the pinch radius and the occurrence of oscillations and a probable breakup of the pinch after the first contraction. At sufficiently strong magnetic fields there is no evidence for contraction of the current.

[1] M. Glicksman and M. C. Steele, Phys. Rev. Letters 2, 461 (1959).

K10. Light as a Plasma Probe. M. BARANGER,* *Carnegie Institute of Technology,* AND B. MOZER,† *Brookhaven National Laboratory.*—The effect of plasma oscillations on atomic spectra is examined. It is shown that they can give rise to satellite lines, disposed symmetrically in pairs about a forbidden line and separated from it by ω_p, the plasma frequency. Their appearance is due to a double transition: first the plasma field induces transition between two close levels with $\Delta l = \pm 1$; then light is emitted, again with $\Delta l = \pm 1$. For ion densities larger than 10^{13} cm^{-3}, it should be possible to measure the plasma frequency and the intensity of the oscillations by observing the satellites. They should start appearing for oscillations appreciably stronger than thermal plasma oscillations, but with total energy still well below the total thermal energy of the gas. For densities smaller than 10^{13} cm^{-3}, the two satellites coalesce, and the effect reduces to excitation of the forbidden line by the plasma field through Stark effect.

* Part of the work was performed while this author was a consultant with General Atomic; support at Carnegie came from the Office of Naval Research.

† Supported by the U. S. Atomic Energy Commission.

K11. Nanosecond Triggering of Air Gaps with Intense Ultraviolet Light. TERRY F. GODLOVE, *Naval Research Laboratory.*—A study of the triggering of a spark-gap switch in air by means of the uv light from an auxilliary spark is presented. The duration of the trigger spark is 6 nanosec, and its peak intensity is sufficient to cause triggering of the main gap at voltages as much as 12% below threshold. The time delay between the light pulse and the breakdown of the main gap has been measured as a function of voltage and the separation of the two gaps for 4 values of the gap spacing d, corresponding to breakdown voltages V_s from 7 to 25 kv. The time delay t_d is found to obey the relation $\log (t_d - t_-) = a - bV$, where a and b are constants, V is the voltage ($V < V_s$), and $t_- = d/v_-$ is the electron drift time. This relation holds only for $t_d < 3t_-$ to $5t_-$, depending on d. As the voltage is reduced to 8% below threshold, the delay increases to $\sim 5t_-$ for the highest uv intensity used. As the voltage is further decreased, t_d becomes very large and statistical in nature. The results are consistent with the view that the photoelectric emission is above that required for a slight distortion of the electric field but below that required for space charge saturation. An initial current density ranging from $\sim 10^{-7}$ to $\sim 10^{-3}$ amp/cm^2 is hypothesized. Electrometer measurements of the average photoelectric current in air as a function of voltage (both accelerating and retarding) have been made and in connection with attenuation measurements (in air, quartz, and LiF) indicate a dominant wavelength of 1000–13000 A.

K12. A method for Computing the Radial Distribution of Emitters in a Cylindrical Source.* W. L. BARR, *Lawrence Radiation Laboratory.*—To obtain the true radial distribution from the observed projected intensity profile of a cylindrical source, one can use inversion formulas if one has an analytic expression to describe the data. If no such analytic function can be found, one must resort to numerical methods. Most previous methods[1–3] suffer from the fact that the effect of random errors in the data is amplified in the differentiation process. This paper describes a method which smooths the effect of random errors by making a least-squares fit of a set of polynomials to an integral over the data. These polynomials were differentiated to yield the desired coefficients. The result is an expandable table of universal coefficients which, in one step, transform the observed data into the desired radial distribution. Results obtained by different methods will be compared, using a steady-state plasma source.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] Kjell Bockasten, Institute of Physics, University of Uppsala, Uppsala, Sweden (unpublished).

[2] R. N. Bracewell, Australian J. Phys. 9, 198 (1956).

[3] W. J. Pearce, *Conference on Extremely High Temperatures* (New York, 1958), p. 123.

K13. Pinch Stability Experiments. K. AITKEN, R. BICKERTON, S. COCKROFT, J. JUKES, AND P. REYNOLDS, *Atomic Energy Research Establishment, Harwell.*—Further results are reported on the surface instabilities or "fluttering" observed in discharges in both the pinch and hard-core geometries. In the pinch case these instabilities are predicted by hydromagnetic theory, and detailed comparison between the observations and theoretical predictions shows fair agreement. The hardcore, although theoretically stable, shows instabilities similar to those observed in the pinch. It has been established by correlation measurements that the wavelength of the dominant mode is equal to the pitch of the magnetic field spiral. By varying the shape of the initially applied axial field, it has been shown that end effects due to the "freezing" of this field in the copper electrodes are unimportant. An explanation of the results is proposed in terms of the finite conductivity of the plasma.

Post-Deadline Abstracts

PD1. Synchrotron Radiation from a Plasma Cylinder.* WILLIAM E. DRUMMOND AND MARSHALL N. ROSENBLUTH, *General Atomic.*†—A numerical evaluation on the IBM 7090 has been made of the synchrotron emission from a plasma cylinder with uniform magnetic field at 40-kev temperature. Previous errors[1] in angular distribution and analytic approximations[2] have been eliminated so that the results should be accurate to a few percent. A convenient fit to the energy radiated is given by saying that the cylinder radiates like a blackbody at frequencies below an effective harmonic of the nonrelativistic cyclotron frequency given by $m_{eff}=0.7(\beta_e BD/1-R)^{1/6}$. Here β_e is the ratio of electron kinetic pressure to magnetic pressure, B is the field in gauss, D the diameter of the cylinder in cm, and R the reflectivity of possible metallic mirrors. A comparison of this loss with thermonuclear energy production in a $D-D$ fusion reactor gives an estimate of the critical β of such a reactor. On the assumption that no other losses are present, that the secondary T and He^3 are utilized, and that radiative and neutron losses are fed back with a thermodynamic efficiency of 33%, one finds $\beta_{tot}=6\times10^3[(1-R)/BD]$. This result is considerably more optimistic than those of Trubnikov[2] partly because of reduced radiation but primarily because of more favorable "economic" assumptions. One would conclude that a $D-D$ reactor with $\beta\sim0.1$ should be feasible on this account.

* Research on controlled thermonuclear reactions is a joint program carried out by General Atomic and the Texas Atomic Energy Research Foundation.

† John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic Division of General Dynamics Corporation, San Diego, California.

[1] Drummond and Rosenbluth, Phys. Fluids 3, 45 (1960).

[2] Trubnikov and Kudryavtsev, Proc. Geneva Conference 31, 93 (1958).

PD2. Cyclotron Emission from Plasmas with Non-Maxwellian Distributions.* G. BEKEFI, J. L. HIRSHFIELD, AND S. C. BROWN, *M.I.T.*—Results of calculations of the cyclotron emission from mildly relativistic plasmas with non-Maxwellian electron distribution functions are described. Two classes of distribution functions are considered: (a) those that decrease monotonically with increasing energy; (b) those with one or more maxima displaced from zero energy. For (a), calculations of the radiation temperature were made from a generalization of Kirchhoff's law for non-Maxwellian distributions, and the emission, over the frequency range in which the self-absorption is large, exceeds by less than a factor of 10 that for a Maxwellian distribution of the same average energy. For (b), negative absorption occurs because the stimulated emission exceeds the absorption and leads to large amplification of the cyclotron radiation, particularly near the peaks of the lower harmonics. As an example, we consider a Maxwellian distribution displaced by a net electron drift velocity that is small compared with the random velocity.

* This work was supported in part by the U. S. Atomic Energy Commission and in part by the U. S. Army Signal Corps, the U. S. Air Force Office of Scientific Research, and the Office of Naval Research.

PD3. Plasma Oscillations and Acceleration of Electrons. JULIAN ANDERSON, *Philco Corporation.*—Radio-frequency oscillations and high-energy electrons are observed in plasma over such a large variation of density, plasma generation, and boundary conditions that their coincidence may represent a basic phenomenon. The occurrence of oscillations of electron density fluctuations $f(u, t)$ and the self-consistent field $\varphi(t)$ are discussed from the viewpoint of the kinetic theories of Vlasov and Landau. Acceleration of electrons by collective interaction is investigated by obtaining the roots of the exact dispersion equation by invoking the chaotic hypothesis, and the Laplace integral for $\varphi(t)$ is then obtained by the theorem of residues. It is found that the field is coherent and damped in the limit $t\to\infty$ only if the group velocity dS/dk does not vanish while, if $dS/dk=0$, the field is undamped, incoherent, and in thermal equilibrium with the electrons. In the case of random motion it is found that the field consists of a single, coherent oscillation near the plasma frequency and that a part of the electrons must be accelerated. The theoretical results are discussed with respect to observations of laboratory discharges, thermonuclear devices, and cosmic rays.

PD4. Recent Results of the NRL Magnetic Compression Experiment.* H. R. GRIEM,† A. C. KOLB, W. H. LUPTON, AND D. T. PHILLIPS, *U. S. Naval Research Laboratory.*—A high-energy plasma is produced in preionized deuterium (0.1 mm Hg) by a current pulse through a single turn coil (length 70 cm, i.d. 5.7 cm, mirror ratio 2:1, peak current 5.5×10^6 A, H_{max} 80 kg in 5 μsec, coil voltage 10 kv, bank voltage 19 kv). Time-resolved measurements of the soft x-ray intensities transmitted by various absorber foils yield an electron temperature which rises very rapidly from 500 ev at 2.5 μsec to a maximum of 1.1 kev at peak current, apparently because of the dissipation of an initially trapped reverse field (~4 kg) as well as the compression. From the bremsstrahlung in the visible follows an electron density of 2.5×10^{16} cm^{-3}. Streak camera observations indicate that the plasma is macroscopically stable throughout this time and well contained. Later, in the first half-cycle, the plasma splits into rotating filaments,[1] and the end losses increase sharply. The electron temperature on the second half-cycle is <300 ev. The impurity level during the first half-cycle is less than 1% because, within the experimental error, there is no excessive soft x-ray radiation.

* Jointly supported by the U. S. Atomic Energy Commission and the Office of Naval Research.

† Physics Department, University of Maryland.

[1] A. C. Kolb and N. Rostoker, abstract K3, this meeting.

PD5. Measurements of the Electron Velocity Distribution in a Hightly Ionized Hollow Cathode Discharge.* W. D. GETTY AND L. D. SMULLIN, *M.I.T.*—The discharge is made by injecting argon gas through a 4-mm o.d. tantalum tube into a vacuum.[1] A magnetic induction of 300–600 gauss is used to collimate the discharge. The gas flow rate is 0.1–100 atm cc/min and the background pressure varies between $0.5–1.0\times10^{-3}$ mm Hg. A Langmuir probe, placed near the visible edge of the discharge, yields a typical density of 2×10^{13} electrons/cc and a temperature of 3 ev. Microwave reflection from the plasma was investigated by illuminating the column at 35 kMc from an open waveguide located 1 cm from the discharge axis. The discharge was varied to determine plasma resonance, which occurs in substantial agreement with the probe results. These measurements indicate an ionization of more than 10%. Approximately two-thirds of the input power is dissipated at the anode; thus about 10% of the electrons have a drift energy of 20–80 v.

* Supported in part by U. S. Army Signal Corps, U. S. Air Force Office of Scientific Research, and Office of Naval Research, and in part by National Science Foundation.

[1] C. Michelson and D. J. Rose, 13th Gaseous Electronics Conference, October, 1960, Monterey, California.

PD6. Time-Resolved Doppler Width Studies in a High-Current Pulsed Discharge. S. A. RAMSDEN, A. G. HEARN, AND B. B. JONES, *Atomic Energy Research Establishment, Harwell.*—A well-known and valid objection to the interpretation of Doppler width measurements in high-current pulsed discharges in terms of ion temperature is the possibility of mass motion of the plasma column. This can lead to a displace-

ment of the line as a whole with consequent broadening. A method is described employing photomultiplier detection whereby it is possible to detect any such displacement. On the assumption of a Doppler profile, the ion temperature and velocity of motion can be determined as a function of time throughout a single discharge. Results are presented for the spark line He II 4686 produced in a high-current toroidal discharge in helium.

Minutes of the Divisional Meeting of the Division of Fluid Dynamics Held in Baltimore, Maryland, November 21, 22, and 23, 1960

THE 1960 Divisional Meeting was held on the campus of The Johns Hopkins University during the three days preceding Thanksgiving. The arrangements for the meeting were made by the Programme Committee consisting of Stanley Corrsin, R. J. Emrich, F. N. Frenkiel, Harold Grad, W. C. Griffith, and C. C. Lin (*Chairman*) and by the local Organizing Committee consisting of Stanley Corrsin (*Chairman*), L. S. G. Kovasznay, and D. E. Kerr. The scientific programme included 5 invited and 55 contributed papers. The 263 registered participants included 212 from out of town.

The spacious and comfortable auditorium of Shriver Hall included two unusually fine features which the audience and speakers enjoyed: the sound system allowed even the most inexperienced speaker to be heard clearly, and spacious, *rigid*, well-lighted blackboards allowed the speakers' symbolic presentations to be seen clearly. Auditorium architects will, it is hoped, pay careful attention to these achievements. The customary informal scientific discussions which play so large a part in the Divisional Meetings were conducted in the lobby and in a coffee-equipped common room in Shriver Hall.

On Monday morning, the participants were welcomed by P. Stewart Macaulay, Executive Vice-President of The Johns Hopkins University. At the Tuesday evening Banquet of the Division held in the Lord Baltimore Hotel following a cocktail hour generously provided by The Martin Company, François N. Frenkiel, Chairman of the Division, presided. M. J. Lighthill, Director of the Royal Aircraft Establishment, England, presented the main address of the evening: "Fluid Dynamics as a Branch of Physics." While not detracting from the achievements of those scientists, from Newton on, who have attempted to formulate our knowledge of the physics of fluids, Mr. Lighthill emphasized that our understanding is only rudimentary; existing formulations are unrealistic, and the most elementary flows of real fluids cannot be described. The audience was, of course, pleased to be commended on its valiant forays against these ancient problems.

Chairmen of the Session were as follows:

A—F. N. Frenkiel
B—Arthur Kantrowitz
C—C. C. Lin
D—H. W. Emmons
E—G. B. Schubauer
F—L. S. G. Kovasznay

Raymond J. Emrich, *Secretary*
Division of Fluid Dynamics

Invited Paper

A1. The Classical Problems of Hydrodynamic and Hydromagnetic Stability. S. Chandrasekhar, *The University of Chicago* (45 minutes).

Contributed Papers

A2. Measurements of Hysteresis on Flow between Rotating Cylinders. D. R. Caldwell and R. J. Donnelly, *The University of Chicago.*—We have used a small rotating cylinder viscometer in which the inner cylinder rotates to measure the torque transmitted by fluid flow in the laminar and supercritical range of speeds. We find that, when the radii of the cylinders are nearly equal, the torque is a unique function of the Reynolds number of the flow regardless of the manner in which the flow is established, provided only that sufficient time is allowed for equilibrium to be reached. In particular we find that the critical speed for transition to cellular flow is identical with speed at which cellular flow reverts to laminar flow. When the gap between the cylinders is large, a small hysteresis in the torque near the critical speed is observed.

A3. On the Stability of a Periodic, Boundary-Free Flow.* T. J. Eisler and W. C. Meecham, *The University of Michigan.*—The stability of a boundary-free, two-dimensional, parallel incompressible flow, whose velocity profile is the cosine, has been investigated using the method of small perturbations. For the boundary condition one imposes the restriction that the perturbations should be bounded. The curve of neutral stability in the αR plane has been calculated for regions of small and large αR, where α is the wave number of the perturbation and R is the Reynolds number of the basic flow. For large αR, solutions of the Orr-Sommerfeld equation have been obtained by expanding in powers of $(\alpha R)^{-1}$. In this region the neutral curve approaches $\alpha = 1$ asymptotically as $R \to \infty$. For small αR a Fourier expansion has been used leading to an

eigenvalue equation involving an infinite determinant of the Hill type. The neutral curve intersects the R axis in this region, giving a critical Reynolds number of order unity. Preliminary calculations indicate that the spectrum of the eigenvalue c, the complex wave velocity of the perturbation, lies along the imaginary axis of the c plane and consists of an infinity of segments separated by gaps.

* Supported in part by the Office of Naval Research and the Signal Corps.

A4. On the Rolling Up of a Vortex Sheet.* F. R. HAMA AND E. R. BURKE, *University of Maryland.*—Validity of the classical result obtained by Rosenhead on the rolling up of a vortex sheet is examined. His computation is found to be doubtful, and the vortex sheet does not actually roll up in a simple way. First, smaller time intervals must be used for the step-by-step integration of the nonlinear development of the vortex sheet. Second, redistribution of the vorticity along the sheet, as it undergoes a sine-wave distortion, has to be taken into account. It is then shown that the vortex sheet rolls up in a more regular manner. Strong concentration of the vorticity, however, does not result. Effect of positive or negative background vorticity on the rolling-up formation is also considered.

* Supported by the U. S. Air Force Office of Scientific Research.

A5. Self-Induced Velocity on a Curved Vortex.* JOHN NUTANT AND F. R. HAMA, *University of Maryland.*—The distribution of self-induced velocity along a curved vortex is investigated analytically as well as by means of an analog experiment of the magnetic field of a current-carrying cable. Results verify a theorem which was intuitively introduced by Hama in his study of detailed process of boundary-layer transition: the induced velocity on a curved vortex is largest in the region where the curvature is largest.

* Supported by the U. S. Air Force Office of Scientific Research.

A6. Spectrum in a Turbulent First-Order Reaction at Large Schmidt Number.* S. CORRSIN, *The Johns Hopkins University.*—On following a theoretical model introduced by Batchelor[1] for turbulent mixing at very large Schmidt number (diffusivity much smaller than kinematic viscosity), a spectral form is deduced for the viscous-convective subrange of the reactant when a stationary, first-order chemical reaction accompanies the mixing. A similar study of the product of reaction does not exclude the possibility of a secondary spectral peak under special conditions.

* Supported by Fluid Dynamics Branch, Office of Naval Research.
[1] G. K. Batchelor, J. Fluid Mech. 5 (1), 113 (1959).

A7. Grid Turbulence at High Reynolds Numbers. A. L. KISTLER AND THOMAS VREBALOVICH, *California Institute of Technology.*—Turbulence intensity and spectral distributions have been measured behind a square mesh grid mounted in the Southern California Cooperative Wind Tunnel, a tunnel of sufficient size and range of operating conditions such that a Reynolds number based on mesh size of 2.4×10^6 was attained. The maximum Reynolds number attained, based on the turbulent microscale and the fluctuation intensity, was 750, a number significantly larger than any produced in previous grid turbulence experiments. The turbulence intensity in the mean stream direction was not equal to the intensity transverse to the stream direction at any Reynolds number. The turbulent energy decayed as the inverse distance from the grid with an effective origin about 10 mesh lengths from the grid. At the higher Reynolds numbers the power spectra of the longitudinal velocity fluctuation showed an extensive region where $E_1(k)\sim k^{-5/3}$ and where the high wave number region of the spectra scaled approximately as predicted by the Kolmogoroff theory. The spectra of the transverse component of the velocity did not conform, however, to that predicted by the theory of local isotropy, having a logarithmic slope somewhat smaller in absolute value than 5/3 in the inertial subrange. The transverse spectra did scale, however, with variables constructed from local transverse turbulence levels and local transverse microscales.

A8. Effects of Inhomogeneity and Shear Flow on Decaying Turbulence in the Final Period. R. G. DEISSLER, *Lewis Research Center, NASA.*—In order to study some of the processes occurring in inhomogeneous and shear-flow turbulence, spectrums for turbulence in the final period were calculated for the following simplified cases: (1) turbulence inhomogeneous in the direction of a uniform mean velocity, (2) turbulence inhomogeneous in a transverse direction, and (3) turbulence homogeneous with a uniform mean velocity gradient. The effect of inhomogeneity was to cause a diffusion of turbulence in the direction of decreasing turbulent intensity. Longitudinal inhomogeneity produced an accumulation of energy mainly in the high wave number (small eddy) portions of the energy spectrum, whereas transverse inhomogeneity did not alter the shape of the spectrum. For homogeneous turbulence with a uniform mean velocity gradient, energy was transferred from the mean flow into the turbulence by a turbulent production term in the spectral equation. At small velocity gradients the spectrum of the production term coincided approximately with the energy spectrum, whereas at higher velocity gradients the production spectrum shifted toward the lower wave number region. Although triple correlations were neglected (final period), a term containing the mean velocity gradient occurred in the spectral equation which was interpreted as transferring energy between wave numbers. As in the case of the energy transfer due to the triple correlations, the effect of this transfer term was to excite the higher wave number regions of the energy spectrum by transferring energy into those regions.

A9. A Statistical Approach to Turbulence Based on Burgers' Model Equation.* D. W. MOOMAW AND W. C. MEECHAM, *The University of Michigan.*—In this report we investigate the statistical properties of some approximate solutions to Burgers' model equation,

$$\frac{\partial u}{\partial t}+\frac{\partial u}{\partial X}=\nu\frac{\partial^2 u}{\partial X^2},$$

and the related time-independent, inhomogeneous equation,

$$u\frac{\partial u}{\partial X}=\nu\frac{\partial^2 u}{\partial X^2}+F(X),$$

where in the first case we suppose the initial "velocity" u to be random and in the second case we suppose the "driving force" $F(X)$ to be a white noise process. Specifically, we imagine $F(X)$ to consist of a sum of a large number n of delta functions with random amplitudes A_i and then consider the case where $n\to\infty$, $\langle A_i^2\rangle\to0$, so that $n\langle A_i^2\rangle$ remains finite. A particular result for certain class of initial process is that the flatness factor of the distribution of $u(X, t)$ may decay rapidly from large values to a value of 2.9 where it stays for some time, then rises slightly above 3.0 and again falls to 3.0 as $t\to\infty$. The velocity by this criterion quickly becomes nearly Gaussian. The statistical properties to be reported show considerable similarity to those of turbulence, despite the fact that the model is one-dimensional and lacks a pressure term.

* Supported in part by the Office of Naval Research and the Signal Corps.

Invited Paper

B1. Some Hydromagnetic Problems Suggested by the Geomagnetic Field. G. BACKUS, *University of California, La Jolla.*

Contributed Papers

B2. Simultaneous Effect of a Magnetic Field and Rotation on Heat Transport by Convection.* YOSHINARI NAKAGAWA, *University of Chicago.*—The effect of simultaneous action of a magnetic field and rotation on the heat transport by convection has been examined experimentally. A layer of mercury was used for the experiment, and the simultaneous effect of a magnetic field and rotation was examined for both types of convection, i.e., the overstable (purely oscillatory convection) and the ordinary cellular convection, which can arise from thermal instability under such circumstances. The results show that the ordinary convection attains a higher efficiency of heat transport in comparison with the overstable convection and that the efficiency of heat transport increases with the strength of the simultaneous action of a magnetic field and rotation.

* Supported in part by the Office of Naval Research.

B3. The Poiseuille Plasma Experiment. H. W. EMMONS, *Harvard University.*—In order to make accurate connection between plasma experiments and magnetohydrodynamic theory, the Poiseuille plasma experiment has been devised. Gas and an electric current simultaneously pass symmetrically through a cylindrical tube. The tube, made of a pile of insulated, water-cooled copper plates, provides accurate measurements of pressure, electric field gradient, and heat transfer distribution as well as over-all data; arc current, gas flow, and pressure. Initial test results with argon and helium, interpreted by a simple mean value theory, show good experimental accuracy and reasonable magnitudes for the plasma transport properties. An attempt at a more accurate (but still approximate analytical) theory leads to difficulties which are discussed and will be resolved in future work.

B4. Weak Planar Interactions between a Periodically Distributed Magnetic Field and a Laminar Viscous Channel Flow. C. H. T. PAN, *General Electric Company* (introduced by R. A. Alpher).—The fully developed laminar, incompressible, two-dimensional, magnetohydrodynamic channel flow through an applied magnetic field of periodic distribution is the subject of this investigation. The viscosity and conductivity are assumed constant and isotropic. Space charge and displacement current are neglected. The transverse component of the applied magnetic field considered is symmetrical with respect to the central plane of the channel. To maintain two-dimensionality, the electric field in the laboratory coordinate system is assumed uniform and normal to the plane of the magnetic field. Linearization is achieved by assuming a small Hartmann number. The first-order induced electromagnetic effects are proportional to magnetic Reynolds number. The flow field is solved as a perturbation of the plane Hagen-Poiseuille flow. The disturbance, which is proportional to the square of the Hartmann number, consists of an increase in pressure drop which is accompanied by distortion in the mean velocity profile and a sinusoidal motion containing a double frequency harmonic. Associated with these are longitudinal and transverse pressure variations. The pertinent parameters are the ratio of the electric field in laboratory coordinates to the intensity of that in the Lorentz frame, the period of the applied magnetic field, and the Reynolds number.

B5. Effects of Current Loops on the Inviscid Velocity Profile in a Two-Dimensional Magnetohydrodynamic Channel.* A. W. CARLSON, *Princeton* AND G. W. SUTTON, *General Electric Company MSVD.*—The effects of end current loops on the velocity profile in a two-dimensional magnetohydrodynamic incompressible, inviscid channel flow has been investigated. The magnetic field and electrodes voltage are assumed constant for all $x>0$; for $x<0$ the channel walls are assumed to be nonelectrical conductors and the magnetic field is zero. A nonuniform electric current field exists in the region about $x=0$; these interact with the magnetic field to cause a nonuniform Lorentz force. The net result is a decrease in velocity at the center line of the channel and an increase of velocity near the electrodes. The changes in velocity are proportional to the magnetic interaction parameter; when this is equal to 0.25, the maximum percentage change in the velocity profile is 10%.

* Supported by U. S. Air Force Office of Scientific Research.

B6. Measurement of Motionally Induced Voltage in Some Magnetohydrodynamic Channel Flows.* W. D. JACKSON, *M.I.T.* (introduced by J. P. Penhune).—The effect of a magnetic field directed transversely to the flow direction of a channeled, electrically conducting fluid is to modify the velocity profile with respect to the corresponding hydrodynamic case. This effect can be measured in terms of the voltage developed between a pair of electrodes or contacts appropriately located on the inner surface of the channel walls. Experimental results obtained with mercury and sodium chloride flows in circular, square, and rectangular channels for both laminar and turbulent flow conditions will be presented and will be shown to give satisfactory agreement in cases where the velocity profile and induced voltage can be predicted.

* This work was supported in part by the U. S. Army Signal Corps, the U. S. Air Force Office of Scientific Research, and the Office of Naval Research.

B7. Diffraction of a Hydromagnetic Wave by a Half Plane. C. S. GARDENER, *New York University* (introduced by Harold Weitzner).—We solve for the diffracted wave which results after a weak plane hydromagnetic shock strikes the edge of a rigid half plane which is parallel to the magnetic field. The solution is given explicitly by elliptic integrals. The solution is derived by an adaptation of the conical-flow method of supersonic aerodynamics. By this method the problem is reduced to a problem of potential theory in two dimensions. We assume that all space, outside a rigid obstacle in the shape of a half plane, is occupied by a medium which is a perfect fluid and a perfect electrical conductor. Initially the medium is at rest and permeated by a constant magnetic field. The field is assumed to be parallel to the half plane and normal to its edge. Then, we assume, a weak plane shock propagates through the medium in a direction normal to the edge of the half plane. The problem is to solve for the flow after the incident wave strikes the edge of the half plane. The solution exhibits an interesting phenomenon, namely, the presence of zones of constant state behind the front of the diffracted wave. This phenomenon is similar to a phenomenon discovered by Weitzner.[1] Weitzner found that similar zones are lacunae in the range of influence given by the fundamental solution of the linearized hydromagnetic equations in two dimensions.

[1] H. Weitzner, Bull. Am. Phys. Soc. Ser. II, 5, 321 (1960); also Phys. Fluids (to be published).

B8. On the Green's Function for Two-Dimensional Magnetohydrodynamic Waves. II. HAROLD WEITZNER, *New York*

University.—Elsewhere[1] the problem of two-dimensional magnetohydrodynamic wave propagation was considered and the Green's function for the linearized Lundquist equations was given for a particular magnetic field configuration. There, with the unperturbed magnetic field in the xy plane, and with all quantities varying with x, y and time only, the Alfvén wave and fast-slow wave are independent. Here, with the direction of unperturbed magnetic field unspecified, but otherwise with the same restrictions, the Green's function, representing the magnetic field, flow velocity, and density resulting from an instantaneous point disturbance, considered as a distribution, is given by algebraic formulas plus standard distributions. The singularity surface for the equations, or ray cone, is described and is similar to that in the special case; and again there is a region inside the wave front with no disturbance. A pure Alfvén wave may no longer be produced, a complicated mixture of Alfvén and fast-slow waves being generated, although as before pure fast-slow waves exist.[2]

[1] H. Weitzner, Bull. Am. Phys. Soc. Ser. II, **5**, 321 (1960).
[2] The separation into modes is discussed by H. Grad in *The Magnetodynamics of Conducting Fluids*, D. Bershader, editor (Stanford University Press, 1959).

B9. Magnetic-Fluid Dynamic Problem of a Shock Wave Attached to a Finite Cone. J. R. BARTHEL AND P. S. LYKOUDIS, *Purdue University* (introduced by C. G. Davis).—When a supersonic stream moves past a sharp-nosed body in the presence of a magnetic field, the shock wave location is dependent on the flow in the electrically conducting shock layer; the flow in the shock layer is in turn dependent on the shock wave location and shape because the flow must satisfy the appropriate oblique shock relations immediately behind the shock. This interaction is considered in the case of flow around a finite cone, assuming a nonconducting free stream, with a uniform, axial magnetic field in the shock layer. The resulting equations are simplified by physical arguments which allow an exact solution for the shock location as a function of radial distance. This solution is restricted to the hypersonic case (thin shock layer) and to moderate distances from the vertex of the cone; viscous and heat conduction effects, as well as variations of density and electrical conductivity, are neglected. This solution is compared with numerical integrations of the equations, accounting for variable density and electrical conductivity, in several typical cases. The singular point at the vertex is discussed in detail.

B10. Cylindrical Magnetohydrodynamic Shock Waves. C. GREIFINGER, *The Rand Corporation* AND J. D. COLE, *California Institute of Technology.*—It is known that, if an axial rod is surrounded by an ionized gas, an inverse pinch effect[1] can be produced by passing through the gas a current which returns along the rod. The azimuthal magnetic field acts like a piston, pushing the plasma away from the rod and leaving behind a cylindrical vacuum region. The plasma boundary is preceded by a shock wave. We consider the case where a uniform magnetic field parallel to the axis is initially present in the gas. A magnetohydrodynamic shock results in this case from the current discharge. If it is assumed that the gas is infinitely conducting and that the discharge current varies linearly with the time, a similarity solution for the resulting flow can be obtained. Two exact integrals of the four magnetohydrodynamic equations can be found, and the problem reduces to the numerical integration of two ordinary differential equations. Results have been obtained for the case $\gamma = 7/5$, and the dependence of the shock speed on the relevant experimental parameters determined. The motion is also analyzed on the basis of the snowplow theory, and the results compared with the exact solution.

[1] O. A. Anderson, H. P. Furth, J. M. Stone, and R. E. Wright, Phys. Fluids **1**, 489 (1958).

Invited Paper

C1. The Oceanic Circulation. H. STOMMEL, *Harvard University.*

Contributed Papers

C2. Vertical Convection in Stably Stratified Water in the Presence of Combined Temperature and Salinity Gradients. A. B. ARONS, *Woods Hole Oceanographic Institution.*—Consider a stably stratified body of water with temperature and salinity both increasing vertically, i.e., the salinity gradient is not large enough to overcome the effect of increasing temperature so that density decreases monotonically in the positive z direction.[1] It is shown both experimentally and theoretically that this system, although gravitationally stable, is convectively unstable owing to the large difference in magnitude between the molecular diffusion coefficients of heat and salt, the former being about two orders of magnitude larger than the latter.[2] The instability tends to manifest itself in its initial laminar form as a set of counter current "fingers" or "tubes" of fluid, fingers of higher salinity water falling downward among fingers of lower salinity water rising from below.

[1] H. Stommel, A. Arons, and D. Blanchard, Deep-Sea Research **3**, 152 (1956).
[2] M. E. Stern, Tellus **12**, 172 (1960).

C3. Film of Experiment Showing Salt Fingers. HENRY STOMMEL, *Harvard University,* AND F. C. RONNE, *Woods Hole Oceanographic Institution* (introduced by C. C. Lin).—A time-lapse motion picture is shown of the formation of salt convective fingers in a laboratory experiment. A sustained waviness of the finger also is seen.

C4. Thermohaline Turbulence. M. STERN AND J. PEDLOSKY, *Woods Hole Oceanographic Institution* (introduced by C. C. Lin).—The columnar motions which are transporting salt between two horizontal plates in a maintained thermohaline convection must be disrupted eventually by self-excited buckling instabilities whose energy source is the available potential energy associated with horizontal variations of salinity in the ascending and descending columns. We first describe the finite amplitude equilibrium field using a model suggested by W. Malkus. A tractable analytic problem is obtained by considering the asymptotic limit where the salinity difference between the two plates (ΔS) and the salt diffusivity (K_s) both approach zero but in such a manner that their ratio is constant. When expressed in nondimensional form, this ratio becomes the eigenvalue for the second instability. The characteristic value problem reduces to an ordinary Mathieu-like equation and leads to an infinite determinant for the critical value of $\Delta S/K_s$. Our iterative calculations to date indicate the possibility of overstable oscillations of time scale proportional to K_s^{-1} as well as neutral disturbances whose phase lines are tilted to the horizontal. We plan to extend these calculations and to determine the preferred mode for the second transition. It is pointed out that this instability occurs at vanishing Reynolds number, and we therefore anticipate additional transition points, leading to aperiodic motions as ΔS is increased.

C5. Convective Circulation in Water Induced by Evaporative Cooling. W. G. SPANGENBERG AND W. R. ROWLAND, *National Bureau of Standards* (introduced by G. B. Schubauer).—Simultaneous orthogonal Schlieren photographs were taken to show the convection currents induced by evaporative cooling from the surface of a tank of water near room temperature. These pictures revealed some hitherto unreported phenomena. They showed that, as a prelude to streaming, the cooled surface film collects along lines causing a thickening of the surface layer and thus establishes areas of instability. The thickened line then plunges as a sheet over its entire length when the stability limit has been exceeded. The plunging lines marking the surface are of continuously changing form. In the top Schlieren view they sometimes appear straight, sometimes curved, branched, or terminated with no apparent regularity of pattern or movement. When the plunging sheets are branched, there is generally no interconnection between the branches to form the tesselated surface patterns so often described. Cellular motions were observed occasionally at particular evaporation rates. Continuous temperature distributions were determined experimentally during the transient cooling period and also after convective circulation had been established to find the gradients involved in establishing the motions. The critical Rayleigh number was estimated to be 1193 by numerical integration of the nonlinear temperature distribution curves. An instability of much smaller magnitude was required to maintain the convective circulation after it had been established.

C6. Turbulence in the Upper Atmosphere. S. P. ZIMMERMAN, K. S. W. CHAMPION, AND S. K. MAJUMDAR, *Air Force Cambridge Research Laboratories.*—Taylor's theory of turbulent diffusion expresses the dispersal of a material component in a turbulent fluid by

$$\langle r^2 \rangle = 2\langle u^2 \rangle \int_0^t \int_0^t R_\xi d\xi dt,$$

where R_ξ is the Lagrangian correlation function. The limiting values of $\langle r^2 \rangle$ are, for small times $(t \to 0)\langle r^2 \rangle = \langle u^2 \rangle t^2$ and for large times $(t \to \infty)\langle r^2 \rangle = 2\langle u^2 \rangle L_\xi t$, where

$$L_\xi = \int_0^t R_\xi d\xi.$$

These relations have been used to develop a theory of the growth of a material cloud in a turbulent atmosphere. The predictions of this theory have been compared with the observed rates of expansion of clouds of chemicals ejected from rockets in the upper atmosphere. The experimental results suggest that, at certain altitudes, the diffusion is predominantly turbulent in nature, whereas at other altitudes the measured diffusion coefficient is in approximate agreement with the predicted molecular diffusion coefficient. These results are consistent with photographic observations of the presence or absence of turbulence. The observed eddy sizes are in agreement with the scales of turbulence predicted by Booker.

C7. Orbital Deceleration and the Derivation of Air Density by Means of Near Earth Satellites.* G. V. GROVES, *University College, London* (introduced by K. S. W. Champion).—Formulas relating air density in the region of satellite perigee to orbital deceleration may be obtained on the assumption that either (a) the eccentricity e is small (less than about 0.2) or (b) that e is large (greater than about 0.012). In the range $0.012 < e < 0.2$, the formulas are found to agree within their respective orders of accuracy. Terms arising from the nonspherical shape of the atmosphere are included. The theory is applied to orbital data from the Discoverer series of satellites to obtain the air density profile in the altitude region of 170 to 270 km.

* This work was supported by the U. S. Air Force Cambridge Research Laboratories.

C8. Decay of Viscous Trailing Vortex.* EMERY GASPAREK AND D. S. DOSANJH, *Syracuse University* (introduced by H. C. ROTHENBERG).—A steady, three-dimensional helical vortex was generated by a rectangular, symmetrical half-airfoil cantilevered from the wall of the circular test section of a low-speed wind tunnel. The radial, tangential, and axial velocity distributions in the trailing vortex were measured with a five-hole pressure sensitive probe at one to eight chord lengths behind the trailing edge of the airfoil. All tests were performed at a Reynolds number based on the free stream velocity and chord length of the airfoil of 10 000. The various experimental velocity distributions were in good agreement with a linearized, axi-symmetric, laminar, viscous vortex analysis due to Newman.[1] The decay of various velocities as well as the growth of the related geometry parameters, however, were found to be 8 to 10 times faster than predicted by the analysis. The maximum amount of circulation which actually rolled up in the trailing vortex was only about 58% of that expected.

* Supported by the National Science Foundation.

[1] B. G. Newman, "Flow in a viscous trailing vortex," Aeronaut. Quart. (1959).

C9. Finite Difference Analysis of Plane Poiseuille and Couette Flow Developments. FLETCHER OSTERLE, *Carnegie Institute of Technology.*—The problem of flow development from an initially flat velocity profile in the plane Poiseuille and Couette flow geometry is investigated for a viscous fluid. The basic governing momentum and continuity equations are expressed in finite difference form and solved numerically on a high-speed digital computer for a mesh network superimposed on the flow field. Results are obtained for the variations of velocity, pressure, and resistance coefficient throughout the development region. A characteristic development length is defined and evaluated for both types of flow. Results indicate that the development length increases with the ratio of wall to mean velocity and that its effect on the pressure development is a minimum for a wall to mean velocity ratio of about 1.35.

C10. Turbulent Couette Flow. WILLIAM SQUIRE, *Southwest Research Institute.*—The author's equations for incompressible turbulent flow[1] are applied to flow between parallel walls in relative motion and to the flow between concentric rotating cylinders. The results of the calculations are compared with the available experimental data.

[1] W. Squire, Appl. Sci. Research 8, 158 (1959).

Invited Paper

D1. Velocity Concentrations in Rotating and Stratified Fluids. R. R. LONG, *The Johns Hopkins University.*

Contributed Papers

D2. Attenuation of Shallow Water Waves.* C. E. GROSCH AND S. J. LUKASIK, *Stevens Institute of Technology.*—The dissipation of the energy of progressive shallow water waves due to the presence of a bottom boundary layer appears as an attenuation of the wave amplitude a that can be represented by $a = a_0 \exp(-kx/h)$, where a_0 is the wave amplitude at $x = 0$,

k is the attenuation coefficient, and h is the water depth. By linearizing the Navier-Stokes equations, the attenuation coefficient is found to be,[1] to terms $O(R^{-4})$, $k_{\text{theoret}} = (\pi/4R)^{-\frac{1}{2}}$ where R is a wave Reynolds number ($R = c\lambda/\nu$ with c the wave velocity, λ the wavelength, and ν the kinematic viscosity of the fluid). Experiments have been carried out to measure the amplitude attenuation coefficient as a function of Reynolds number over a range from 10^6 to 10^8. At each Reynolds number the wave amplitude was measured at several points along a 240-ft wave channel for a water depth of 3.25 in. using a float gauge coupled to a rotary differential transformer. The values of k were obtained by fitting a least-squares line to the values of the wave amplitude measured at various positions. Typical wave amplitudes were 0.025 in. The results show that the functional form of $k(R)$ predicted by linearized theory is correct but that $k_{\text{expt}}/k_{\text{theoret}} = 1.78 \pm 0.06$. The effects of nonlinearities in the Navier-Stokes equation and of the nonlinear free surface condition on the anomalously high values of the observed attenuation are discussed.

* Work supported by U. S. Navy, Bureau of Ships.
[1] F. Biesel, *La Houille Blanche* (1949), p. 630.

D3. Measurement of Shallow Water Wave Shear Stress. S. J. LUKASIK AND G. W. ZEPKO, *Stevens Institute of Technology*.—A pendulum balance flush-mounted in the botton of a 240-ft long wave channel has been used to measure the shear stress exerted by a plane progressive shallow water wave. The balance consists of an aluminum plate 3 in. $\times$24 in. $\times$0.064 in. thick whose motion is recorded by means of a differential transformer. Simultaneously the wave amplitude at the balance is recorded, thus providing the potential fluid velocity as well as the pressure forces exerted on the balance. Subtraction of the pressure force from the total force measured by the balance leaves the wave shear force. Measurements have been made over a range of wave Reynolds numbers ($R = c\lambda/\nu$) for the purpose of examining the physical mechanism responsible for the anomalously large wave attenuation coefficients that have been observed.[1] Results to date indicate an order of magnitude agreement between the energy loss measured by a direct observation of the wave amplitude attenuation and that obtained by integrating the product of the shear stress and the potential velocity over a wave period. Also, these appears to be no boundary layer separation occurring during any part of the wave period.

* This work supported by the U. S. Navy, Bureau of Ships, and the Office of Naval Research.
[1] C. E. Grosch, L. W. Ward, and S. J. Lukasik, Phys. Fluids **3**, 477 (1960); see also preceding abstract.

D4. Interaction Between Gravity Waves and a Shear Flow. B. A. HUGHES AND R. W. STEWART, *University of British Columbia* (introduced by A. M. Patterson).—Three major properties of a surface tension-gravity wave system have been examined experimentally and compared with existing theories: viscous decay in the absence of mean flow compared to the theory given in Lamb,[1] No. 348; propagation velocities in the presence and absence of flow, compared to Lamb, No. 267, and the change of wave energy on crossing a stable Couette shear flow, compared to two theories—one obtained from the Navier-Stokes equations including terms up to second order in wave slope, the other, following previous authors, assuming any direct interaction of the waves with the shear flow to be negligible. For wave numbers less than 1.8 cm^{-1}, it was found that the viscous decay rate and propagation laws agree with theory to within the experimental error, and the interaction measurements fit the theory with the nonlinear term included rather than the traditional theories. Results indicate, however, that an anomalous region of wave properties exists for wave numbers near 2.7 cm^{-1}.

[1] H. Lamb, *Hydrodynamics*, (Cambridge University Press, Cambridge, England, 1932), 6th ed.

D5. On Expansion and Contraction of Capillary Jets of Newtonian Liquids. S. MIDDLEMAN AND J. GAVIS, *The Johns Hopkins University* (introduced by S. Corrsin).—Laminar jets of Newtonian liquids are found to contract or to expand upon ejection from capillary nozzles depending upon conditions of ejection and fluid properties. The ratio of final jet diameter to nozzle diameter is a function of Reynolds number and a weak function of Weber number. At Reynolds numbers lower than 16, the jets expand; above 16 they contract. At Reynolds numbers below 5, expansion becomes independent of Reynolds number at a radius of 1.06 if the Weber number dependence is removed. At Reynolds numbers above 150, contraction becomes independent of Reynolds number at a radius ratio of 0.87. These results are explained by means of the momentum and energy equations for the motion. The terms leading to expansion are comparable to relaxing normal stress terms. The existence of relaxing normal stresses in Newtonian liquid jets leads to some questions concerning the origin of normal stresses which are thought to be responsible for the more common observation of expansion in viscoelastic liquid jets.

D6. Surface Tension Effects in Steady Two-Dimensional Cavity Flow about Slender Bodies. S. H. SCHOT, *David Taylor Model Basin* (introduced by A. Borden).—Tulin's linearized cavity flow theory[1] is extended to include surface tension effects at the cavity interface for the case of zero cavitation number. An integro-differential equation is set up for the cavity source distribution and solved by a perturbation method using the surface tension as a small parameter. The cavity shape is worked out explicitly for the slender wedge, and results indicate that the surface tension makes the cavity spring from the body with a discontinuity in slope. The treatment is extended to body shapes for which the cavity detachment point is not known *a priori*. Postulating continuous slope at the body-cavity juncture leads to an equation for the detachment point in terms of the body shape parameters. The result is identical with that obtained by Tulin[2] under different assumptions and neglecting surface tension. A conjecture of Tulin is verified that in this theory there exist convex body shapes with more than one detachment point.

[1] M. P. Tulin, David Taylor Model Basin Rept. No. 834 (1953).
[2] M. P. Tulin, "New developments in the theory of supercavitating flows," in the *Proceedings of the Second Symposium on Naval Hydrodynamics* (presented in August, 1958—to be published).

D7. A Lagrangian Solution of the Cavity Collapse Problem. RONALD S. BRAND, *University of Connecticut* (introduced by M. Holt).—The problem considered is that of the spherically symmetric collapse of an empty cavity in a compressible inviscid liquid which is initially at rest and at constant pressure. A solution is assumed in the form

$$M(h,t) = M^{(0)}(h,t) + \alpha M^{(1)}(h,t) + \alpha^2 M^{(2)}(h,t) \cdots,$$

where M is the cube of the radial distance to any fluid particle identified by its h coordinate, t is time, and α is a constant determined by the pressure at infinity. Solutions are given through $M^{(2)}$, and it is shown that no theoretical difficulty will be encountered in obtaining solutions to any order. The path of the cavity boundary $r(0,t)$ as computed from this solution agrees well with a numerical solution of the Eulerian equations.

D8. Use of Electrochemiluminescence for Visualizing Fields of Flow.* R. C. GESTELAND, B. HOWLAND, W. H. PITTS, AND A. S. RICHARDSON, JR., *M.I.T.*—A platinum hydrofoil is immersed in a flowing, alkaline solution containing luminol (5-amino-2, 3-dihydrophthalazinedione) and H_2O_2. Anodic current replaces the usual chemical catalysis, generating a bright surface glow with intensity distribution controlled by mass transfer. This clearly displays the flow at the boundary

layer without disturbing it. A methanolic solution also shows the flow behind the hydrofoil; the luminescence leaves the anode and extends downstream along the trail of fluid that has passed through the boundary layer for a distance determined by the acidity. The subsequent history of parcels of fluids passing by any part of the hydrofoil can thus be traced when the current is delivered in pulses. Fluid may be recirculated; operation with organic solvents of low kinematic viscosity is possible. Pictures will illustrate laminar and turbulent boundary layers, various wakes, and vortex streets.

* Supported in part by U. S. Army Signal Corps, U. S. Air Force Office of Scientific Research, and Office of Naval Research.

D9. Quantitative Analysis of Two-Dimensional Flow by Means of Streaming Birefringence.* S. P. SUTERA AND HAROLD WAYLAND, *California Institute of Technology.*—Streaming birefringence measurements made with tobacco mosaic virus solutions in an eccentric cylinder system are compared with an orientation theory of streaming birefringence in general two-dimensional flow. It is concluded that, for sufficiently dilute solutions of macromolecules with a short relaxation time, the orientation theory is valid and can be used to interpret the flow from the optical measurements, provided the complete character of the flow is known along at least one streamline.

* Supported in part by the National Science Foundation.

D10. A Pitot Probe for Observation of Boundary Layers in Pits of Fluid Dynamic Origin. D. T. WILLIAMS AND W. J. LARKIN, *University of Florida.*—In connection with a study of the fluid-dynamic phenomenon of pit formation in ablating bodies, it became necessary to observe the distribution of fluid velocity in boundary layers within depressions so small as to prevent the use of the conventional type of boundary layer rake. A pitot probe was developed for this use. It consisted of a pair of nickel capillary tubes each with one end closed, and a hole in the side as near to the closed end as possible, soldered back to back. This probe device was successfully used to measure the direction and velocity of vortex air flow within a pit of fluid dynamic origin. For use in determining the velocity distribution within the boundary layer under the vortex in the pit, velocity determinations were made very close to the surface. A special procedure was used in which the lower portion of the probe was lowered into a hole drilled for the purpose. A series of observations in which the validity of thus modifying the shape under investigation has led to the conclusion that such a procedure is valid if the pit is large compared to the probe size.

Invited Paper

E1. Hydrodynamics of Superfluid Helium. R. J. DONNELLY, *University of Chicago.*

Contributed Papers

E2. Electron and Ion Density Profiles Ahead of Shock Waves in Argon.* H. D. WEYMANN AND B. TROY, *University of Maryland.*—Earlier work[1] showed that electrostatic precursor signals are associated with electrons diffusing ahead of the shock front. In order to obtain more detailed information on the profiles of the electron and the ion densities, a new probe, capable of measuring relative densities in the range 1 to 10^{-3}, was employed. It was found that, up to distances of about 5 cm from the shock front, the electron density and the ion density are equal due to ambipolar diffusion. For distances between 5 and 50 cm the electron density is much larger than the ion density and decreases exponentially with the distance from the shock front. A theoretical treatment of the problem shows that in this latter region $d \ln n_e/dx = -U_s/D_e$ (n_e = electron density, U_s = shock velocity, D_e = electron diffusion constant). Good agreement between theoretical and experimental results can be reached if D_e is calculated with the electron temperature behind the shock front.

* Supported in part by the U. S. Air Force Office of Scientific Research ARDC.
[1] H. D. Weymann, Phys. Fluids **3**, 545 (1960).

E3. Shock Tube Investigation of the Ionization of Cesium Vapor.* A. F. HAUGHT, *Princeton University.*—A conventional pressure-driven shock tube was used to produce ionizing shocks in a uniformly heated test section containing argon and vaporized cesium. The concentration of the cesium vapor was sufficiently low for the shock equations of the argon buffer alone to be valid, and a region of constant temperature, pressure, and density was obtained behind the shock. In addition, the low cesium concentration insured that only argon-cesium collisions were effective in the ionization process. Measurements of luminosity delay time and shock Mach number were obtained from revolving drum camera photographs. The luminosity time data were fitted to a simple collision theory model involving a phenomenological activation energy. The activation energy (2.29 ev) evaluated from the data lies about halfway between the first excitation potential (1.38 ev) and the ionization potential (3.89 ev). This differs from the results of various observers[1,2] working with rare gas systems where activation energy was very nearly equal to the first excitation potential. Since the activation energy is not some characteristic energy level of the cesium, it is suggested that the ionization reaction proceeds by any one of a number of multiple stage processes, each involving successive excitation of the cesium.

* Supported in part by the Office of Naval Research.
[1] H. Petschek and S. Byron, Ann. Phys. **1**, 270 (1957).
[2] W. Roth and P. Gloersen, J. Chem. Phys. **29**, 820 (1958).

E4. Measurements of Nonequilibrium Radiation from Shock Waves.* J. CAMM, B. KIVEL, R. TAYLOR, AND J. D. TEARE, *AVCO.*—Measurements have been made of the nonequilibrium radiation from shock waves in air using photoelectric gages, a spectrograph, monochromators, and a bolometer. For these measurements a combustion-driven shock tube 24 in. in diameter was used to produce shocks having speeds of 6.8 mm/μsec in air at an initial pressure of 20 μ of Hg. Since the maximum gas temperature is computed to be about 25 000°K before dissociation and vibrational excitation take place, significant amounts of radiation might possibly be found in the spectral region of from 300 A to 25 μ. The radiant intensity in a direction normal to the shock is about 0.4 w/cm^2 sr, and most of the radiation originates within 5 cm of the shock front.

* Work supported by U. S. Air Force.

E5. Ionization Processes in High-Temperature Flow Fields.* H. BLOOMBERG, C. LIU, AND R. GOULARD, *Bendix Systems Division.*—The ionization effects observed in high-temperature flows are governed by energy-density fields. When the electron concentration is not dominant, as is the

case for air below 10 000°K, the energy-density field is controlled mostly by the relaxation processes of atomic dissociation and recombination. In this paper a quantitative study is made of these phenomena in the case of the air flow around bodies re-entering the earth's atmosphere. The different parameters controlling the departure from equilibrium are analyzed, and their range of interest is discussed in some detail. A simple stability criterion is applied to the relaxation processes behind the shock and around the body, and nonequilibrium ionization is superimposed to the energy field.

* Supported by the Army Rocket and Guided Missile Agency.

E6. Transition Probabilities for Nitric Oxide in the Far Ultraviolet.* J. W. DABIER AND M. J. WILLIAMS, *Cornell Aeronautical Laboratory* (introduced by W. H. Wurster).—Nitric oxide was heated in a shock tube up to 2200°K behind the reflected shock wave. Absorption spectra of the (0,1), (0,2), (0,3), and (1,4) bands of the gamma system were photographed, using a continuum light source and a medium quartz spectrograph. The NO was diluted in an argon bath in volume ratios from 0.08% to 10%. This was necessary for two reasons. First, it was essential to photograph the spectra before the NO decomposed detectably. An earlier study by Freedman and Daiber verified that argon dilution slows the NO decomposition rate because of reduction in NO partial pressure. The effectiveness of this dilution was confirmed by the absence of O_2 absorption on the resulting spectrograms. Secondly, high pressures were used to obliterate the rotational structure, and at the required pressures pure NO is totally absorbing. The wavelength-integrated absorption coefficients for each band were determined. From these data, the electronic oscillator strength was calculated to be $0.0034\pm25\%$. This value is greater than the 0.0024 derived by Weber and Penner and by Bethke, from gas cell measurements at room temperature of the $\gamma(v',0)$ sequence in the vacuum ultraviolet, and the value of $0.001\pm50\%$ based on the emissivities of 4000°K air by Keck *et al.* For the NO beta system, which was not observed on any spectrogram, the electronic oscillator strength was inferred to be less than 0.006. This value does not discriminate between Keck's -0.006 and Bethke's 0.0015.

* Supported by U. S. Air Force Office of Scientific Research.

E7. Shock Tube Determination of Dissociation Rates of Oxygen.* J. P. RINK, H. T. KNIGHT, AND R. E. DUFF, *Los Alamos Scienitfic Laboratory.*—The rate of dissociation of oxygen in Xe-O_2 mixtures was measured over a temperature range of 3000°K to 6000°K. An x-ray densitometer was used to measure the density during the dissociation process behind a shock wave. It was possible to match the experimental data with theoretical density profiles over a wide range of compositions and initial conditions. The reactions considered were $O_2+M\rightleftarrows 2O+M$, where M can be Xe, O_2, or O. If we consider theses species as third bodies, the measured recombination rates k_r in cc^2 mole^{-2} sec^{-1} were $4.7\times10^{17}\ T^{-1}$, $1.6\times10^{18}\ T^{-1}$, and $4.8\times10^{18}\ T^{-1}$, respectively. The third body efficiencies of O_2 and O relative to Xe are 3 and 10. Experimental conditions were such that an accurate measurement of the exponent of the temperature could not be made. However, since the data showed it to be within the limits of $-\frac{1}{2}$ and -2, a value of -1.0 was arbitrarily chosen. The agreement between results reported here and previous work demonstrates the potential utility of this method for kinetic studies of other reactions.

* Work done under the auspices of the U. S. Atomic Energy Commission.

E8. Measurement of Electron Density in Rarefied Gas Streams by Microwave Interferometry.* F. O. SMETANA AND H. R. PASS, *University of Southern California* (introduced by R. L. Chuan).— A K-band microwave interferometer was constructed for the purpose of examining the efflux from a relatively small, hypersonic, low-density nozzle, the efflux having been excited to an active condition in the nozzle by a high-power VHF discharge. The phase shifts obtained were interpreted as electron density according to the usual weak signal theory. Uniform distribution was assumed. Both nitrogen and argon were used as test gases. Because the VHF energy added per particle is highest, the recombination times the largest, and the attenuation of the microwave beam the least, highest phase shifts can be expected at relatively low pressures. This was found to be the case. Unfortunately, however, at these pressures the nozzle flow became subsonic because of very high viscous losses. At higher pressures where hypersonic flow was established, data were not obtained because of severe attenuation of the beam. At the test conditions electron densities in argon were about 100 times those in nitrogen, approaching 2×10^{13} per cc for neutral particle densities of about 3×10^{15} per cc. The effect of dielectric bodies in the stream also was investigated qualitatively. Application of this system to the measurement of electron density in the region of bodies in hypersonic flow is planned.

* Supported in part by the joint program of the Office of Scientific Research, Office of Naval Research, Arnold Engineering Development Center, and the U. S. Air Force Cambridge Research Laboratories.

E9. One-Dimensional Electrogasdynamics. M. C. GOURDINE, *Plasmadyne Corporation* (introduced by Che-Jen Chen).—The steady one-dimensional flow of a compressible fluid carrying a slight excess charge (ions) in the presence of a parallel applied electric field is analyzed. The electric field accelerates the ions which in turn transmit momentum and energy to the neutrals through collisions. Approximate equations describing this process are derived, and analysis yields criteria for "choking" the flow. For example, if electric power is added to the flow, it tends to "choke" (is driven towards Mach one) whenever

$$\frac{U_i}{u}>\frac{\gamma+1}{\gamma-1}\frac{1}{1+\gamma M^2}$$

where U_i is the ion drift velocity, u is velocity, M is Mach number, and γ is the ratio of specific heats. Thus, to prevent "choking" the charge carriers should have a low mobility or be massive compared to the neutrals. Solutions are given for power extraction as well as power addition. A solution consists of finding the change in state of the gas, the charge distribution, and the space-charge induced electric field.

E10. Stagnation-Point Heat Transfer in an Arc-Heated Argon Jet.* W. L. BADE AND R. R. JOHN, *AVCO.*—Similarity of the Lees[1] boundary-layer equations were calculated assuming the viscosity-temperature relation[2] $\mu=\mu_s(T/T_s)^{1-\alpha}$. The results gave a stagnation-point heat-transfer correlation for high-temperature argon

$$q_s\simeq0.99(\rho_s\mu_s)^{\frac{1}{2}}\beta^{\frac{1}{2}}(h_{ss}-h_w),$$

where ρ denotes density, $\beta\equiv(du_s/dx)_s$ the stagnation-point velocity gradient, and $(h_{ss}-h_w)$ the stagnation-enthalpy difference across the boundary layer. The stagnation-point heat flux from a subsonic (~Mach 0.5) jet of arc-heated (~8000°K) argon to a flat surface was measured. Jet enthalpy and velocity were estimated from mass-flow and energy-balance data assuming one-dimensional flow. The experimental heat flux was ~25% higher than the theoretical prediction. Jet nonuniformity may have been responsible for this discrepancy.

* Sponsored by Ballistic Missile Division, ARDC.

[1] L. Lees, Jet Propulsion **26**, 259 (1956).

[2] For argon, $\alpha\sim0.25$; cf. I. Amdur and E. A. Mason, Phys. Fluids **1**, 370 (1958).

Contributed Papers

F1. Effect of Moderate Cooling on Transition on a Blunt Body in Simulated Hypersonic Flow.* ROGER DUNLAP AND A. M. KUETHE, *The University of Michigan.*—Transition Reynolds numbers were observed on a cooled 9-in. diam brass sphere with hypersonic pressure distribution in a "shroud tunnel." Reynolds numbers $a_s D/\nu_s$ (a_s is stagnation speed of sound) up to 24×10^6 were obtained by pressurizing the tunnel. The sphere was cooled internally with liquid nitrogen. The state of the boundary layer was determined by means of a Stanton tube at various positions forward of the 45° point (the flow was sonic at about 42°). For a surface rms roughness around 1 μ-in. and no appreciable condensation of water vapor or carbon dioxide on the surface, the maximum transition Reynolds number, Reynolds number Re_s, corresponding to transition at the 45° point, shows relatively small variation for temperature ratios, T_w/T_s, down to 0.44. Temperature ratios down to 0.38 were attained but in the range between 0.38 and 0.44 transition appeared to be correlated with carbon dioxide condensation on the surface. Minute dust particles deposited on the surface also caused transition in many of the observations. Comparison with other experiments in wind tunnels, shock tubes, and in flight indicate that within the range of our experiments the effect of surface cooling in decreasing the threshold roughness for transition is probably responsible for the observed "transition reversal" in the subsonic region on blunt bodies in hypersonic flow.

* Supported by Aeronautical Research Laboratories, U. S. Air Force Research Division.

F2. Aerodynamic Forces Due to Hypersonic Viscous Flow. L. TALBOT, C. STUDERUS, AND S. SCALA, *General Electric Company MSVD.*—Interest in the aerodynamic stability of bodies during high-altitude hypersonic flight has produced a need for information on how the aerodynamic forces are altered by the appearance of large viscous effects. These effects are particularly important for sustained hypersonic flight. In this paper, consideration is given to the problem of estimating the axial force, normal and pitching moment coefficients produced by viscous shear stress, and induced pressures on the spherical nose of a hypersonic vehicle when the flow over the body is asymmetric. Exact solutions of the hypersonic laminar continuum boundary layer equations were first obtained. These were then utilized to determine boundary layer characteristics such as the nominal, displacement, and momentum thicknesses as well as the shear stress acting over the surface. General relationships also were derived which yielded the separate contributions of the shear forces and of the induced pressures to the viscous aerodynamic forces when the vehicle is at an angle of attack to the free stream. The exact boundary layer solutions were then introduced into these relationships. The calculations were performed over a wide range of hypersonic flight conditions, and the results are presented in a useful parametric form.

F3. Comparison between Theory and Flight Test on an Ablating Heat Shield. S. GEORGIAV AND M. B. T. GEORGE, *AVCO* (introduced by Bennett Kivel).—Flight test results on a glass-plastic composite heat shield are compared to the theoretical predictions. The theoretical predictions were based on the postulate that the ablation of the glass can be calculated independently of the ablation of the plastic and vice versa. The good agreement between the theoretical predictions and the flight tests indicate the correctness of the postulated ablation mechanism. One important consequence of the ablation mechanism is that the temperature of the ablating surface is controlled by the temperature of the thin liquid layer formed by the flow of ablating glass. It is shown that this ablation theory can be applied to any composite consisting of a plastic material which is reinforced with a glassy material. Thus the calculation of the ablation characteristics of these composite materials is greatly simplified.

F4. Experimental Production of a Zero Gravity Environment. E. T. BENEDIKT AND R. LEPPER, *Northrop Corporation.*—A "zero-g tower" or "gravidrome" 87 ft in height has been erected at NORAIR for the experimental investigation of hydrodynamic and heat transfer phenomena in a zero gravity environment. The device is based on the principle of the encapsulated cell previously suggested.[1] The cylindrical cell containing the liquid to be investigated is placed inside a larger container capable of being evacuated down to 1 μ Hg pressure. By means of an appropriate release mechanism the first cell as well as the outer capsule are set free simultaneously at the top of the tower. Whereas the fall of the outer container is decelerated due to aerodynamic drag, the motion of the inner cell approaches, for all practical purposes, free fall conditions. According to theoretical predictions,[2] the duration of the fall and the dimensions of the test system are such that it allows the setting in of the configuration of a liquid typical of a zero gravity environment. Observation of the system under investigation is accomplished by means of cinematographic camera attached to the outer capsule. A series of experiments was conducted with J.P.4 (rocket fuel) and mercury. As demanded by the theory, the meniscus of the former liquid assumes a concave spherical shape, whereas mercury conglomerates into a (freely floating) sphere. The time required for the above typical zero gravity configurations to be attained is consistent with the predictions of footnote 2.

[1] E. T. Benedikt, Bull. Am. Phys. Soc. Ser. II, 5, 129 (1960).
[2] E. T. Benedikt, J. Am. Rocket Soc., 159 (February, 1959).

F5. Turbulent Structure of Gaseous Detonation.* D. R. WHITE, *General Electric Research Laboratory.*—Normal and overdriven detonations in $2H+O_2+2CO$ have been studied in a shock tube at initial pressures from 0.1 to 1.4 atm. Measurements have included pressure, density obtained interferometrically, and luminosity whose intensity is shown to be proportional to [CO][O]. Strongly overdriven waves are one-dimensional and are followed by the calculated equilibrium state. Self-sustaining detonations are followed by a lower-than-calculated pressure and density and a supersonic flow. Furthermore, the reaction zone is invariably turbulent. In an examination of the implications of this turbulence, a Chapman-Jouguet wave is considered as one with the minimum velocity of propagation which will satisfy the conservation relations for turbulent flow at the rear of reaction zone. It is shown that this minimum (C-J) velocity is slightly greater than that calculated one-dimensionally and that the final state attained following the decay of turbulence can lie either on the "strong" or "weak" detonation branch of the Hugoniot curve. Intermediate states, including the one-dimensional C-J state, do not represent stable solutions. The self-sustaining detonation, which corresponds to the weak detonation solution, appears as a special case of a C-J detonation. Manifestations of this turbulent structure are pointed out in the work of others, as well as in the data reported here.

* This research has been partially supported by the U. S. Air Force.

F6. Contact Zone Phenomena in Shock Tube Flows.* W. J. HOOKER, *General Electric Research Laboratory.*—We have studied shock wave-contact front-mixing zone phenomena in a 4-cm-diam shock tube over a range of initial driven gas pressure extending from 3×10^{-3} to 10^{-2} mm Hg. The hot flow duration in shocked argon was measured by the selective optical absorption of the 2350 cm^{-1} fundamental vibration-rotation band of the carbon dioxide driver gas. These times

varied from 1½% of theoretical predictions at 10^{-1} mm Hg to 46% at 10^{2} mm Hg. The shape of the contact front has been determined with the use of individual, radially spaced platinum thin film heat gages mounted on a slender cylinder spanning the shock tube on a diameter. The contact front is shown to be a turbulent, planar disturbance even at initial driven gas pressures of 10^{-1} mm Hg. The spatial extent of the mixing zone has been studied in detail and is shown to penetrate as far behind the location of the theoretical contact surface as it does ahead of it. In the Mach number interval of 5–10 in argon no systematic dependence on initial pressure is observed for measured shock velocity vs measured diaphragm pressure ratio.

* Partially supported by the U. S. Air Force.

F7. Turbulent Spots and Laminar Boundary Layer Oscillations in the Shock Tube Boundary Layer.* W. P. THOMPSON, *Lehigh University*.—Thin-film wall temperature gauges of approximately ½- by 0.015-in. dimensions have been placed on a 12-in. long glass plate in the ceiling of a shock tube of 4- by ¾-in. cross section. The gages are at various positions with respect to the sidewalls and leading edge of the plate. At a shock Mach number of 1.22 in 1 atm of nitrogen, the jump to constant wall temperature characteristic of the laminar boundary layer is observed. Shortly after shock arrival at the gage, and upon the arrival of an acoustic pulse generated by the trailing edge of the glass plate when the shock passes it, rather regular small oscillations in wall temperature are suddenly superimposed upon the laminar step function. These oscillations damp out smoothly, the boundary layer remaining laminar until disturbed gas which has passed over the leading edge of the glass plate has reached the gage. At higher shock Mach numbers up to 1.55 in 1 atm of nitrogen, laminar oscillations also are observed, though without the definite origin in time seen for weaker shocks. Occasionally the wall temperature is observed to rise sharply from the laminar value to peak and to decay smoothly to a new constant value. A later transition to fully turbulent boundary layer is then observed. This peaking and decay repeats on successive gages along the glass plate and is interpreted as the passage of a turbulent spot over the gage. Presumably the effect has not been observed by others working at higher shock strengths because the laminar flow times are too short to permit spot growth to observable size.

* Supported by the National Science Foundation.

F8. Shock Wave Curvature at Low Initial Pressures.* R. E. DUFF AND J. L. YOUNG, *Los Alamos Scientific Laboratory*.—The shape of the primary shock wave in a shock tube has been measured in a continuation of an investigation of the performance of a shock tube at low initial pressures.[1] Measurements were made by recording the time of arrival of the shock wave in argon at an array of piezoelectric detectors along a diameter of a 1½-in. i.d. shock tube operating at an initial pressure of 0.34 mm Hg. The following conclusions were drawn from the results: (1) shock wave tilt was negligibly small; (2) shock wave curvature is independent of shock strength from $M_s=1.6$ to 6.0; (3) the shock front shape is nearly that of a paraboloid of revolution; and (4) the axial extent of the curved shock is approximately 1mm. If one assumes that the rate of change of pressure in the divergent flow behind a curved shock is the same for all streamlines, a shock front shape can be derived which is similar to that observed.

* Work was done under the auspices of the U. S. Atomic Energy Commission.

[1] R. E. Duff, Phys. Fluid 2, 207 (1959).

F9. Traveling Shock and Jet Flow Interaction.* D. S. DOSANJH AND T. M. WEEKS, *Syracuse University* (introduced by W. R. Frederickson).—The interaction of a traveling shock front and opposing axisymmetric turbulent jet flow was recorded in a 6-in×6-in. shock tube by optical techniques. Three jets of ¼-, ½-, and 1-in. diameters, operated at different stagnation pressures exhausted into the shock tube. The nature of the bulge which the shock front develops due to its interaction with the opposing jet flow is examined. The flow region behind the traveling shock exhibited radiating compression wavelets of discrete frequencies. Their wavelengths are dependent upon the jet diameter. Quantitative analysis of the interferograms established that the flow region behind the shock front developed a few alternating compression and rarefaction regions. They are strongest along the axis of the jet flow, exhibiting density levels much different from that normally expected behind the corresponding shock alone. The compression and rarefaction region immediately behind the shock seems to be the source of the intermittency of the radiating compression wavelets. The extent of each compression and rarefaction region is also dependent on the jet diameter.

* Supported by the Office of Ordnance Research, U. S. Army.

F10. Hydrodynamics and Molecular Motions.* P. C. MANGELSDORF, *Woods Hole Oceanographic Institution*.—A generalization of Stokes' law has been found which applies to the flow velocity averaged over a spherical surface described in a viscous imcompressible fluid which is in a steady state of motion. Stokes' law holds so long as the surface encloses all inhomogeneities and all loci at which external forces are applied. This theorem may be applied to the statistical flow pattern around a molecule drifting in a fluid under a steady applied force. The correlations thus deduced are found to be characteristic of the random thermal motions also, implying the existence of large "Brownian surges" in the fluid at equilibrium.

* Supported in part by ONR through University of Chicago.

F11. Application of Electromagnetic Wave Theory to an Anatomical Discovery in the Arterial System. HARRY LOBEL, *Nebraska-Iowa Electrical Council*.—Blood flow is sometimes designated as being non-Newtonian. Recent developments indicate that this may be due to mechanical rather than vitalistic characteristics. For example, at the mouths of arteries branching from the aorta are funnel-shaped nozzles. On stimulation, these nozzles adjust their contour to streamline varying flows of blood. Malfunction results in eddy currents. The dynamics of these nozzles demonstrates the inadequacy of Newton's third law. For a dynamic model, pulsations are introduced into elastic tubes filled with fluid. The frequencies of pulsations are varied. At the proper frequency, the pulsations become resonant. In resonance, pressure is minimum for a given flow; in "dissonance," pressure is hypertensive for the same flow. In resonance, pressure and flow are mathematically related in accordance with Newton's third law. In dissonance, the concepts of action and reaction as developed by Newton are completely inadequate. There are two kinds of pressure in dissonance: one is a resistive pressure that derives the fluid; the other is a useless "reactive" pressure. The vector sum of these responses if the "impedance." Newton's third law has no more application to pulsating hydraulic flow than Ohm's law has to alternating electricity. Without differentiating between the resistive and reactive components of pressure, no theory of hydraulics is rational.

MEETINGS AND DEADLINES THROUGH JANUARY 1962

Place	*Meeting dates*	*Deadline date*
Washington	April 24–27	February 10
Mexico City	June 22–24	April 7
Chicago	November 24–25	September 22
Los Angeles*	December 27–29	October 20
New York	January 24–27, 1962	undecided

Abstracts for the meeting marked with an asterisk are to be sent to Professor H. A. Shugart, University of California, Berkeley 4, California, and must reach his office not later than the corresponding deadline date. Abstracts for the other meetings listed above are to be sent to Karl K. Darrow, American Physical Society, Columbia University, New York 27, New York, and must reach his office not later than the corresponding deadline date. Take note that abstracts mailed the day before deadline day often fail to arrive in time: the last postal delivery of the day usually comes to our office before 2 p.m. For meetings handled at this office, *allow at least two days for abstracts sent by airmail from points east of the Mississippi, and longer for those sent from farther west.* Abstracts postmarked (at the point of dispatch) on deadline day are instantly rejected. No abstract postmarked (at the point of dispatch) on deadline day ever reaches the office on time, nor does any abstract postmarked at any point west of the Rockies on the day before deadline day. Some abstracts arrive with covering letters dated three or more days before the postmark; it may be a good idea for you to put your abstract into a United States mail box with your own hands. Finally, if time is scant, fold your abstract and mail it in an envelope of size $9\frac{1}{2}$ by $4\frac{1}{4}$ inches or thereabouts; for if you mail it in a "manila" envelope large enough to accommodate it without folding, it may very well arrive after the deadline. *The privilege of contributing papers to meetings of The American Physical Society is restricted to the members of the Society and to nonmembers whose papers are sponsored by members.*

SECTIONAL MEETINGS AND TOPICAL CONFERENCES (see pages 183 and 184)

Syracuse	New York Section	April 14–15	—
Ithaca	Photoconductivity	August 21–24	March 31
Schenectady	Gaseous Electronics	October 11–13	August 25

RULES AND INSTRUCTIONS FOR THE PREPARATION OF ABSTRACTS

The Council has ordered that abstracts shall be not longer than two hundred (200) words or the equivalent thereof. In reckoning equivalence, a footnote is equated to ten words or to its actual length in words, whichever is the greater; each line in a table to ten words; a "display" formula—one that requires a line to itself—is an expensive luxury equated to forty words. By-lines are not counted as part of the 200 words, and therefore addresses are condensed to the minimum in them. If you want to spend a lot of your precious 200 words in describing your exact location and the exact compartment of your organization in which you work, you have that privilege.

Two copies of each abstract must be sent to the appropriate office. They must be typewritten; *one must be an original*, the other may be an original or a carbon copy. *Carbon copies will not be accepted in lieu of originals:* they smear. *Abstracts* (including titles, by-lines, and footnotes) *must be double-spaced:* single-spaced manuscripts are too crowded to permit the editorial markings to be made with ease and clearness. *Each abstract must be confined to a single page:* if it is too long for a single page it is too long to be printed. If we receive an abstract typed on two pages, we print only its first page. *Write each abstract as a single paragraph:* the suppression of paragraphs costs time and labor to the editors. *Do not use very thin paper:* a sheet of very thin paper may cause extraordinary trouble when mixed with sheets of reasonable thickness. *Tables too broad to fit into one column of the Bulletin will be left out.* The American Institute of Physics will bless you if you type first the title of your abstract in lower-case with capitalized initials, then your name in capitals, then the name of your institution in lower-case underlined with capitalized initials. It is a pleasure to report that those who qualify for this blessing are increasing in number but are still quite a bit short of 100% of the total. Issues of the *Bulletin* are always appreciably delayed because the editors have to do what the authors should have done.

Remember the rule of the Council that, if an author submits more than one abstract, all but one must go into the Supplementary Programme. In enforcing this rule, an abstract is credited to the author whose name appears first in the by-line.

It has now become an expensive business to make any change in an abstract, even the smallest, after it has been received. By order of our Council "A change in an abstract will be permitted only at the discretion of the Secretary or his deputy, and only if TEN DOLLARS is enclosed with the letter in which the change is requested." As heretofore, an abstract will not be withdrawn from proof unless the asker sends ten dollars with his request.

New Instructions

(*a*) *If it is wished that two abstracts be scheduled consecutively, write on the first "To be scheduled before abstract ..... by ....." and on the second "To be scheduled after abstract ..... by ....."*

(*b*) *In general, all instructions about an abstract should be typed at the bottom of the page that has the abstract on it, never in a covering letter. Covering letters get separated from abstracts!*

(*c*) *If a member insists that his paper be scheduled for a particular day or not on a particular day, he will get his wish, but usually at the price of having his contribution included in a session to which it is irrelevant.*

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